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March 2020

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Simulations of Short-Term Exposure to NO_2 and $PM_{2.5}$ to Inform Capture Efficiency Standards

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March 30, 2020

Summary

The California building code requires all new or renovated residential dwelling units to have kitchen exhaust ventilation to manage air pollutants and moisture generated during cooking. Current performance requirements are specified as a minimum airflow and maximum sound level. This report presents an analysis to support consideration of adding a capture efficiency requirement to the code. The analysis uses a physics-based simulation model to calculate air pollutant concentrations in homes that result from cooking and the inflow of outdoor air, mediated by loss and removal process including deposition, dwelling unit ventilation, and the use of a range hood with varying levels of capture efficiency. Calculated pollutant concentrations are compared to relevant, health-based guidelines. The analysis considers the highest 1-hour concentration of nitrogen dioxide (NO_2), which is a product of natural gas combustion and the highest 24-hour concentrations of fine particulate matter ($PM_{2.5}$) which is emitted in substantial quantities from frying, broiling and grilling among other cooking activities. For NO_2, the analysis considers cooking of a dinner for 3-4 persons consisting of pasta, meat sauce, a par-boiled vegetable, and baked garlic bread. For $PM_{2.5}$, the analysis considers a day in which breakfast emitted particles at the 80th percentile and lunch and dinner entailed particle emissions at the 50th percentile of cooking emission events reported in the literature. Model simulations were performed to determine the level of range hood capture efficiency that will allow these cooking scenarios to occur in the vast majority (>99%) of new homes being built in California while maintaining pollutant concentrations below the health-based guidelines, if the range hood is used throughout cooking. All homes were assumed to have dwelling unit ventilation at the rate required in the building code. Simulation model input parameters were specified using a Monte Carlo approach to represent a range of housing characteristics, outdoor conditions, and indoor pollutant dynamics. Simulation results suggest that requiring a minimum capture efficiency of at least 70% is needed to avoid unacceptably high NO_2 (1-h average concentration of 100 ppb or higher) and at least 60% to avoid unacceptably high $PM_{2.5}$ (24-h average of 25 $\mu g/m^3$ or higher). These results were driven by multi-family homes, which have a smaller volume of air to dilute any pollutants not captured and removed at the cooking area, resulting in higher concentrations.

1. Introduction

The Building Energy Efficiency Standards (BEES), which comprise Part 6 of the California Building Code (Title 24) requires all new or renovated residential dwelling units to have kitchen exhaust ventilation to manage the indoor air quality challenges of pollutants, moisture and odors generated during cooking. The code allows for either a range hood to be installed above the cooktop or an exhaust fan elsewhere in the kitchen space, with different requirements for minimum airflow but the same requirement for maximum sound level at the minimum airflow setting. Research by Lawrence Berkeley National Laboratory (Berkeley Lab) suggests that in practice the kitchen ventilation requirement is almost always satisfied by a range hood or an over the range microwave (OTR) with integrated exhaust fan. Any reference to a range hood in this report should be considered as applying also to OTRs. A code-compliant range hood must provide at least 100 cubic feet per minute (cfm) or 50 liters per second (L/s) of exhaust flow with a certified sound rating of 3 sone or less. The airflow must be verified on site or the range hood must be certified to meet the airflow requirement under a standardized test protocol. Certification of test results is done by the Home Ventilating Institute (HVI), which provides certified results in an online product directory. (A known gap in this quality assurance framework is that most range hoods are tested only at 25 Pa duct static pressure whereas the code requires that the devices be certified at 62.5 Pa; that issue is not considered or addressed in this report.)

The goal of this report is to inform consideration of changes to the BEES to specify a required level of range hood capture efficiency, rather than only focusing on airflow and sound requirements. The report describes and presents results of simulations conducted for the purpose of determining a capture efficiency that will keep combustion and cooking-generated air pollutants from reaching unhealthful levels as long as the range hood is routinely used. Simulations focused on two cooking-related indoor air pollutants: NO_2 from natural gas burners and $PM_{2.5}$ from frying and broiling on gas or electric burners.

The use of capture efficiency as the performance metric would enable kitchen ventilation solutions that do not rely solely on high airflows that increase energy use – both for the fan power and to condition the additional air brought into the home to make up for the higher airflows. Currently, there is limited capture efficiency data through HVI. However, with the recently established ASTM (2018) E-3087 standard test method for measuring range hood capture efficiency, it is expected that capture efficiency performance data will soon become more readily available.

Singer et al. (2012) was the first of several studies in the past decade to measure range hood capture efficiency. That study estimated a mean capture efficiency of 55% based on measurements of 15 range hoods installed in California homes. Logue et al. (2014) modeled the acute NO_2 concentrations in California homes assuming that all used a range hood during cooking (but not after) and the range hood in every home removed 55% of the combustion pollutants. With universal range hood use, the estimated fraction of homes exceeding the 1-hour NO_2 standard was 18 to 30%, i.e., large enough to raise serious concerns about the efficacy of range hoods currently in homes.

A recent modeling study by O'Leary et al. (2019b) used $PM_{2.5}$ to set recommendations for range hood airflow and capture efficiency in English houses, because of the importance of cooking as an indoor source of $PM_{2.5}$, and also because of the association between $PM_{2.5}$ and elevated risk of adverse health effects.

In this report, we present a new analysis that was conducted to determine the capture efficiency needed to control NO_2 emitted from natural gas cooking burners to meet health guidelines in the vast majority of new California homes. In addition, the analysis considered $PM_{2.5}$ emitted during cooking regardless of the cooking fuel used, i.e. assuming that the same PM would be produced by the meals considered whether they were cooked with gas, propane or electric burners.

2. Methods

2.1 Overview of Approach

The indoor air quality implications of varied range hood performance levels were assessed using computer simulations of pollutant emissions and removal processes to determine time series of concentrations in homes with cooking. The simulation framework considers emissions from cooking and entry of pollutants with outdoor air, and accounts for removal by kitchen ventilation, continuous dwelling unit ventilation and deposition to surfaces. The simulations assume that range hoods are used at least for the duration of all cooking events and also consider the effect of range hoods being used for 10 min after cooking has ended. Simulations are conducted in a “Monte Carlo” fashion in which key input parameters are selected from distributions at the start of the time series calculation for each individual home. Input parameters include home size and number of bedrooms (which are used in the assignment of the code-required dwelling unit ventilation rate), outdoor air pollutant levels, and deposition rates. Details about the simulation model and parameter distributions are provided in the following paragraphs and sub-sections.

The goal of the simulations was to determine the level of range hood performance that allows substantial cooking to occur in every new home built in California while maintaining pollutant concentrations below health-based guidelines, if the range hood is used. In consideration of findings from prior work and an assessment of the air pollutants that are most likely to exceed guidelines, the analysis focused on short-term nitrogen dioxide (NO_2), which is emitted at substantial rates by gas burners, and fine particulate matter ($PM_{2.5}$), which is emitted at substantial rates during food preparation by frying, grilling and broiling. Electric coil burners can also emit NO_2 but the rates are much lower than from gas burners (Fortmann et al., 2001); NO_2 from electric burners is thus not considered. (Induction burners are even cleaner, as they should have no NO_X emissions since they none of the equipment reaches the high temperature needed to break the molecular nitrogen bonds and limited data suggest they also have much lower ultrafine particle emissions compared to gas or electric resistance burners.) The analysis did not explicitly consider whether $PM_{2.5}$ is emitted only from cooking with appliances that combine cooktops and ovens under the range hood, or if some of the $PM_{2.5}$ is emitted from ovens that are separate or other cooking appliances such as toasters, toaster-ovens, and countertop electric grills. However, since a single range hood capture efficiency (CE) is assumed in each set of simulation runs, the analysis implicitly assumes that all emissions occur from cooking appliance situated under the range hood. Since this is not the case for most countertop appliances (e.g. toasters, toaster ovens, electric grills, etc.) or from ovens that are not integrated with the cooktops in range units, this assumption effectively focuses on cooking from cooktops and range ovens. The analysis also does not consider ultrafine particles – which are emitted by gas and electric burners and during cooking – or potentially irritating or hazardous organic gases emitted during cooking, e.g. acrolein. The analysis of highest 1-h NO_2 concentrations considers cooking of a single meal of pasta and meat sauce, broccoli and garlic bread with quantities suitable for 3-4 persons. The analysis of 24-h $PM_{2.5}$ considers cooking three meals that all emit substantial, though not extreme quantities of $PM_{2.5}$, in a single 24-h period.

Sets of simulations – in which input parameter values were selected from specified distributions to represent conditions across California new homes - were run for several discrete levels of CE. For each CE level, the output of the simulation set was an estimate of the fraction of California new homes that would exceed the following health-based air pollutant guidelines under the conditions modeled.

- NO_2: 1-hour maximum of 100 ppb (California Air Resources Board 2016)
- $PM_{2.5}$: 24-hour average of 25 ug/m^3 (World Health Organization 2006) and 35 ug/m^3 (US Environmental Protection Agency 2012)

The analysis examined new, single family detached, single family attached, and multi-family homes. It was assumed that each home is ventilated precisely at the rate required in California's Building Energy Efficiency Standards, Part 6 of the Title 24 building code (California Energy Commission 2016), henceforth described as "Title 24." Each home type was assigned a distinct floor area distribution and breakdown of natural gas or electric cooking fuel. For homes that use natural gas cooking fuel, NO_2 concentrations were simulated for 4 h from the start of cooking and the maximum 1-h average NO_2 concentration was calculated. $PM_{2.5}$ concentrations were modeled for 24 hours with emissions from the cooking of breakfast, lunch, and dinner. The same $PM_{2.5}$ emission rates were assumed for both natural gas and electric range use. Outdoor NO_2 and $PM_{2.5}$ concentrations were sampled from distributions developed from ambient monitoring data. Distributions for $PM_{2.5}$ and NO_2 penetration factors, deposition rates and emission rates were determined from values reported in the literature.

The assumptions for the Monte Carlo simulation were as follows: that operation of the range hood reduces the cooking or burner pollutant emissions by the specified CE rate; that air in the house is at all times perfectly mixed (and emissions are instantaneously mixed into the full volume of the home); range hood operation both removes cooking and burner pollutants directly by plume capture and also by providing additional dwelling unit ventilation; and the same pollutant emissions (essentially meaning the same meals) are cooked in each residence, irrespective of size and occupancy.

2.2 Mass Balance Model

The following mass balance equation was used to simulate indoor NO_2 and $PM_{2.5}$ concentrations resulted from cooking:

$$\frac{dC}{dt} = P\left(\frac{Q}{V} + \frac{Q_{RH}}{V}\right)C_o + (1 - CE)\frac{E}{V} - \left(\frac{Q}{V} + \frac{Q_{RH}}{V} + k_d\right)C \qquad (1)$$

The indoor concentration was calculated at 1 min resolution (Δt = 1-min) using Equation (1):

$$C_t = C_{t-1}e^{-k\Delta t} + \left[P\left(\frac{Q}{V}+\frac{Q_{RH}}{V}\right)C_o + (1-CE)\frac{E}{V}\right]\frac{1-e^{-k\Delta t}}{k} \qquad (2)$$

where $k = \frac{Q}{V} + \frac{Q_{RH}}{V} + k_d$. $\frac{Q_{RH}}{V}$ is the range hood airflow rate normalized by the house volume and is applied for the full duration of all cooking events and for an additional 10 minutes during some simulations. When the range hood is not in use, $Q_{RH} = 0$.

The initial indoor concentration was calculated using Equation 3:

$$C_{t=0} = \frac{P\left(\frac{Q}{V}\right)C_o}{\frac{Q}{V}+k_d} \qquad (3)$$

All inputs are defined in the table below. Since the number of combinations is large (~12 million), each of the parameters were randomly sampled with replacement for a total of 50,000 simulations. Each home simulation returns the maximum 1-hr concentration (rolling mean) for NO_2, and the daily average concentration for $PM_{2.5}$. Selected model runs were performed using 100,000 simulations to confirm that 50,000 simulations are adequate for predicting the percentage of homes exceeding a certain health guideline.

Table 1. Model input parameters.

Variable	Units	Description
C	g/m^3	Indoor concentration
C_o	g/m^3	Outdoor concentration
V	m^3	Volume of home, calculated from floor area and an assumed ceiling height of 2.5 m
P	-	Penetration efficiency
k_d	1/h	Deposition rate
Q	m^3/h	Ventilation rate
Q_{RH}	m^3/h	Range hood airflow rate
CE	-	Range hood capture efficiency
E	g/h	Emission rate

2.3 Model Parameters

2.3.1 Housing Data

The numbers of single-family and multi-family homes built each year in California were obtained from a 2019 report by the Construction Industry Research Board, or CIRB (Construction Industry Research Board 2019). Between 2011 and 2019, CIRB estimated that 55% of all housing units built in California were multi-family. Single-family homes were further divided into two types, detached and attached, according to data reported by the 2017 American

Housing Survey (US Department of Housing and Urban Development 2018) for California homes built since 2010. The 2017 American Housing Survey (AHS) also provided data on the floor area distribution of California new homes, which were modeled using a lognormal distribution with geometric mean (GM) and geometric standard deviation (GSD) as shown in Table 2 and Figure 1. AHS (2017) reported the percentage of homes that use natural gas as the cooking fuel by home types. Table 2 shows that it is twice as common for single-family detached homes to use natural gas as the cooking fuel, compared to multi-family homes. The majority (59%) of new multi-family homes in California use electricity as the cooking fuel.

Table 2. Housing characteristics.

	Single-Family Detached	Single-Family Attached	Multi-Family
% of New Construction	35%	10%	55%
Floor Area (ft^2)	GM = 2,435 GSD = 1.45	GM = 1,615 GSD = 1.45	GM = 914 GSD = 1.45
Cooking Fuel – Natural Gas	84%	60%	41%

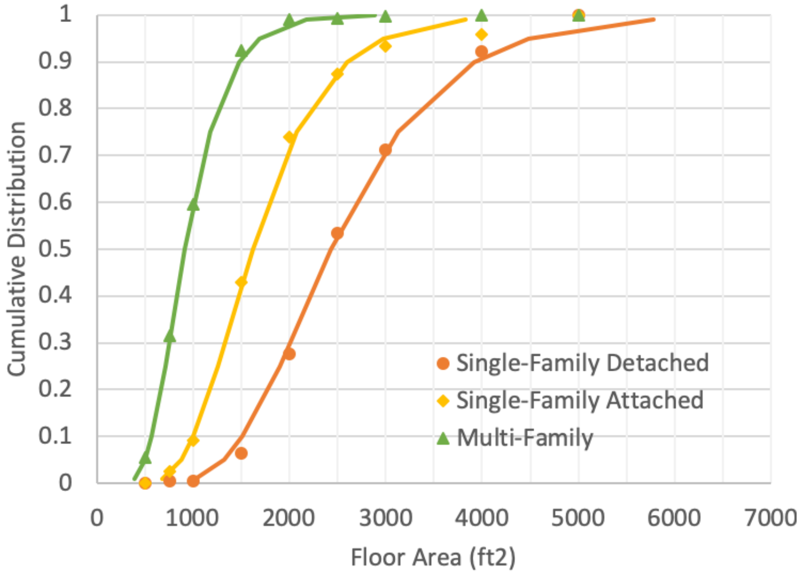

Figure 1 Distribution of floor area of three types of housing: single-family detached, single-family attached, and multi-family. Data points indicate values from American Housing Survey (2017). Lines indicate the approximate lognormal distribution with GM and GSD as described in Table 2.

Title 24 (2016) specifies a requirement for total ventilation airflow Q_{total} (cfm) for low-rise residential dwellings based on the floor area A_{floor} (ft^2) and the number of bedrooms (N_{br}):

$$Q_{total} = 0.03A_{floor} + 7.5(N_{br} + 1) \tag{4}$$

For homes with no bedrooms (i.e. studio or efficiency apartments), N_{br} was set to 1 when calculating Q_{total}. For the simulations, N_{br} was sampled based on floor area using Table 3, which shows N_{br} as a function of floor area for the three housing types using 2017 data from the AHS national housing statistics (US Department of Housing and Urban Development 2018). From a recent study of new single-family detached homes in California (Chan et al. 2019), 5-bedroom homes were common[1]. Because AHS (2017) only reported statistics up to 4 bedrooms, the "4 or more" category for the single-family detached was further divided into 4-bedroom and 5-bedroom using percentages from the recent California study.

Table 3. American Housing Survey 2017 data on number of bedrooms and floor area.

	Floor Area (ft^2)								
Number Bedrooms	<500	500–749	750–999	1000–1499	1500–1999	2000–2499	2500–2999	3000–3999	≥4000
Single-Family Detached									
1	--	28%	9%	1%	1%	0%	0%	0%	0%
2	--	50%	49%	23%	10%	6%	4%	3%	2%
3	--	17%	37%	65%	66%	48%	36%	24%	18%
4	--	5%	5%	10%	23%	45%	42%*	22%*	24%*
5	--	0%	0%	0%	0%	0%	18%*	51%*	56%*
Single-Family Attached									
1	38%	46%	17%	3%	0%	0%	0%	0%	0%
2	62%	44%	68%	52%	29%	18%	0%	13%	0%
3	0%	10%	16%	42%	62%	58%	60%	42%	35%
4	0%	0%	0%	4%	9%	24%	40%	45%	65%
Multi-Family									
0	20%	4%	0%	0%	0%	0%	--	--	--
1	65%	70%	39%	11%	3%	0%	--	--	--
2	16%	25%	56%	67%	58%	42%	--	--	--
3	0%	1%	5%	21%	39%	58%	--	--	--
4	0%	0%	0%	1%	0%	0%	--	--	--

* indicates percentages were adjusted using a recent field study (Chan et al. 2019) to subdivide the "4 or more" category into 4- and 5-bedroom single-family detached homes.

-- indicates no data from AHS (2017) on multi-family homes with floor area >2,500 ft^2 and no single-family homes <500 ft^2 in simulations.

Air exchange rates (1/h) were calculated as follows:

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[1] Healthy Efficient New Gas Homes (HENGH) measured indoor air quality in 70 new California single-family detached homes with mechanical ventilation. Among homes with floor area between 2,000 and 2,499 ft^2, 30% of the homes had 5 bedrooms. Among homes with floor area >3,000 ft^3, 70% of the homes had 5 bedrooms.

$$AER = \frac{Q_{total}}{A_{floor} \times H} \tag{5}$$

where H is the ceiling height, assumed to equal 8.2 ft (2.5 m) for all homes. Figure 2 shows the floor area distributions and calculated air exchange rates used for single-family detached, single-family attached, and multi-family homes. Multi-family homes were modeled with slightly higher air exchange rates than single-family: 0.39/h (mean, multi-family) versus 0.35/h (mean, single-family attached) and 0.33 (mean, single-family detached). These variations result because the fixed airflow required for each bedroom translates to a higher air exchange rate in the smaller multifamily homes.

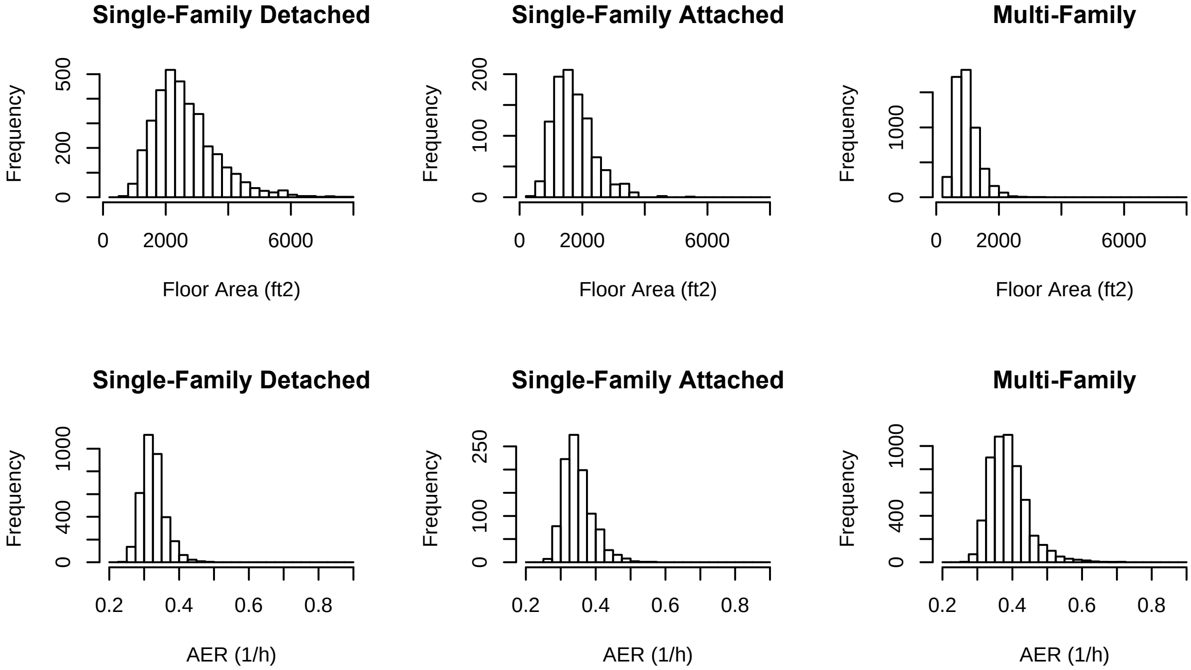

Figure 2. Floor area and air exchange rate modeled for single-family detached, single-family attached, and multi-family homes.

2.3.2 NO_2 Emissions

The analysis for NO_2 was based on the burner use and fuel consumption measured by Berkeley Lab for a meal of pasta with meat sauce, blanched broccoli and garlic bread (unpublished data). Figure 3 and Figure 4 shows the composite number of burners and fuel use (kBTU/h) for the following elements of meal preparation

- Pasta: Heat water to boil, add pasta, reduce heat to cook pasta (29 min burner use)
- Meat sauce: Sautee beef and onion on medium, add sauce, simmer (28.5 min burner use)
- Garlic bread: Preheat oven and bake (14 min of burner use)
- Broccoli: Boil water on high, turn to low to cook broccoli (10 min burner use).

The meal has a total of 82 minutes of burner operation. The average fuel use per minute of burner operation is 7 kBTU/h. In the simulations, the meal was simplified as 4 burners operating for 21 minutes with a constant emission rate of 7 kBTU/h per burner or 28 kBTU/h total.

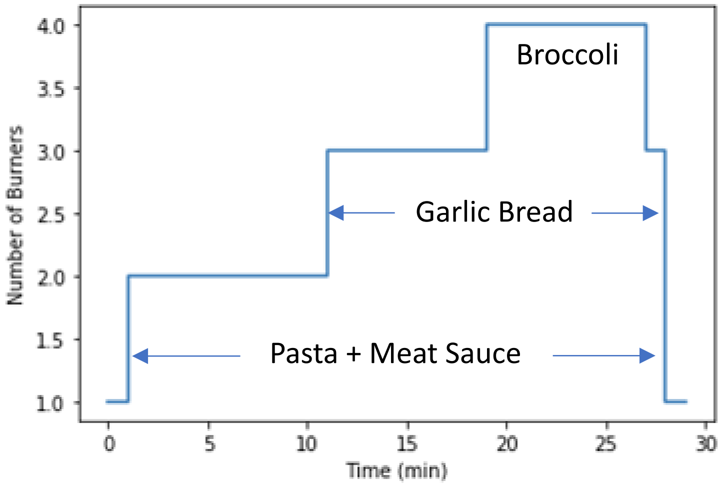

Figure 3. Time series of the actual number of burners used to prepare a pasta meal. A simplified scenario of 4 burners operating for 21 minutes was assumed in the simulation.

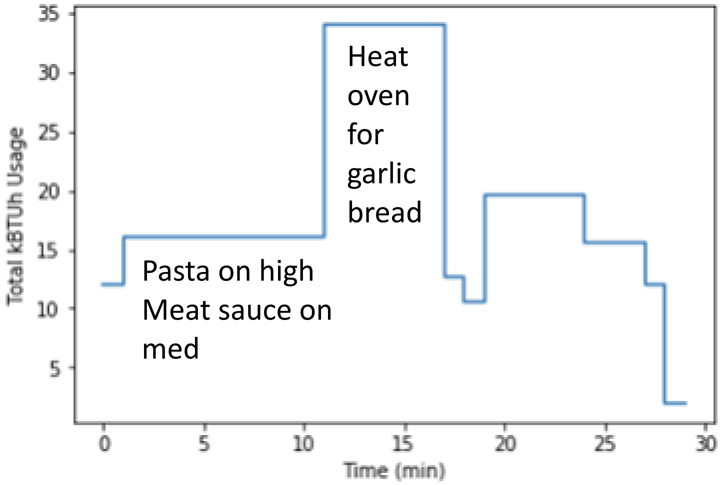

Figure 4. Time series of the actual fuel used (kBTU/h) to prepare a pasta meal. A simplified constant fuel usage of 28 kBTU/h over 21 minutes was used in the simulation.

The analysis of Logue et al. (2014) had varied cooking durations and burner use for dinners based on an online survey conducted by Berkeley Lab (Klug et al. 2011). Figure 5 shows burner-minute for dinners that were modeled assuming two cooktop burners used plus oven use in half of the homes. Cooking durations for the cooktop and oven were modeled using lognormal distributions determined from the online survey. The total of 82 minutes of burner operation modeled for the pasta meal corresponds to 75th percentile of the distribution. The pasta meal and associated NO_2 emission rates constitute a challenging meal but one that could occur routinely in any giving dwelling unit.

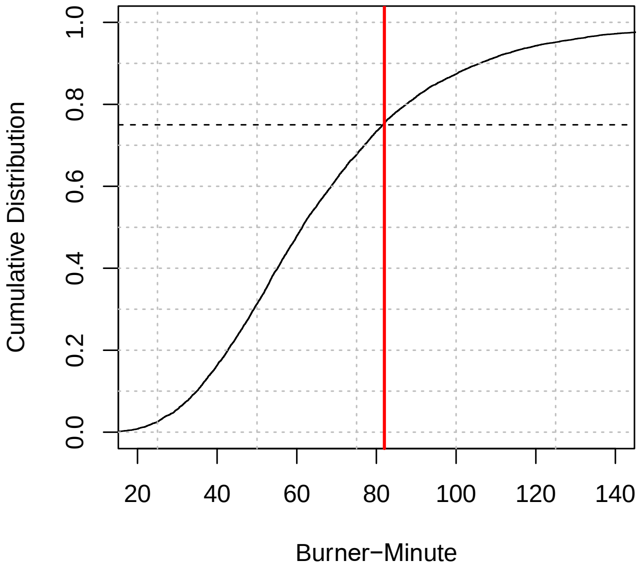

Figure 5. Distribution of burner-minute for dinners modeled by Logue et al. (2014). The pasta meal (82 burner-minute) used in this simulation is indicated in red for comparison.

For each simulation run, NO_2 emissions (g/h) were calculated by multiplying the fuel use of 28 kBTU/h by a fuel normalized NO_2 emission rate (ng/J), selected from a distribution developed from in-home measurements. Fuel normalized NO_2 emission rates were measured by Singer et al. (2017) in nine homes using scripted operation of natural gas cooking burners that included boiling and simmering on the stovetop and oven use. In that study, a mass balance modeling approach similar to the one used in the current analysis was used to determine fuel normalized NO_2 emission rates from time-resolved concentrations of NO_2 and other combustion pollutants. Most of the fuel normalized NO_2 emission rates reported by Singer et al. (2017) ranged between 5 and 15 ng/J, with a geometric mean of 10 ng/J. In this simulation, NO_2 emissions were sampled from a triangular distribution with mode of 10 ng/J and min–max range of 7–22 ng/J.

2.3.3 $PM_{2.5}$ Emissions

$PM_{2.5}$ concentrations were modeled over a 24-hour period during which three meals were cooked and all three had substantial $PM_{2.5}$ emissions. The modeled mass of $PM_{2.5}$ emitted per meal is as follows:

- Breakfast: bacon, eggs and hash browns, 19 min, 100 mg;
- Lunch: stir-fry of chicken and vegetables, 17 min, 50 mg;
- Dinner: pasta Bolognese, 20 min, 50 mg.

These emitted mass and cooking duration values were adapted from data on scripted meals. Breakfast is based on unpublished measurements made at Berkeley Lab that estimated emissions from frying of bacon, eggs, and hash browns to be roughly 85 mg; these were rounded up to 100 mg. O'Leary et al. (2019a) reported average emissions of 53.4 and 53.2 mg of $PM_{2.5}$ for the meals noted; these were rounded to 50 mg/meal.

$PM_{2.5}$ emitted from cooking is highly variable with cooking style (pan, temperature, etc.), ingredients, utensils used, stove characteristics, and the inherent stochastic nature of $PM_{2.5}$ generation. To confirm that the emission rates used in this study were not extreme, we compared them to emissions reported in other studies. Figure 6 shows $PM_{2.5}$ mass emitted from three cooking studies (Fortmann et al. 2001; He et al. 2004; Zhang et al. 2010) as previously summarized by Hu et al. (2012), and from O'Leary et al. (2019a).

In comparison to the literature-reported PM emission factors plotted in Figure 6, the 100 mg assumed for breakfast was roughly at the 80th percentile and the 50 mg for lunch and dinner were in the middle of the reported data.

As another check, we considered the distribution of cooking event emissions determined from analysis of time-resolved $PM_{2.5}$ concentrations in 18 California apartments (Chan et al. 2018); that study identified 836 emission events from 224 days of monitoring data. While the emission events included all indoor sources, many of them were likely cooking related. The analysis found emitted mass in the 18 California apartments to range from 1 to 154 mg, with a mean value of 30 mg (median of 12 mg). The 100 mg (breakfast) and 50 mg (lunch and dinner) modeled roughly correspond to the 90th and 80th percentile of the emitted mass per event estimated by Chan et al. (2018).

The selected meals and associated $PM_{2.5}$ emission rates collectively constitute a challenging day of cooking but one that could occur routinely in any giving dwelling unit.

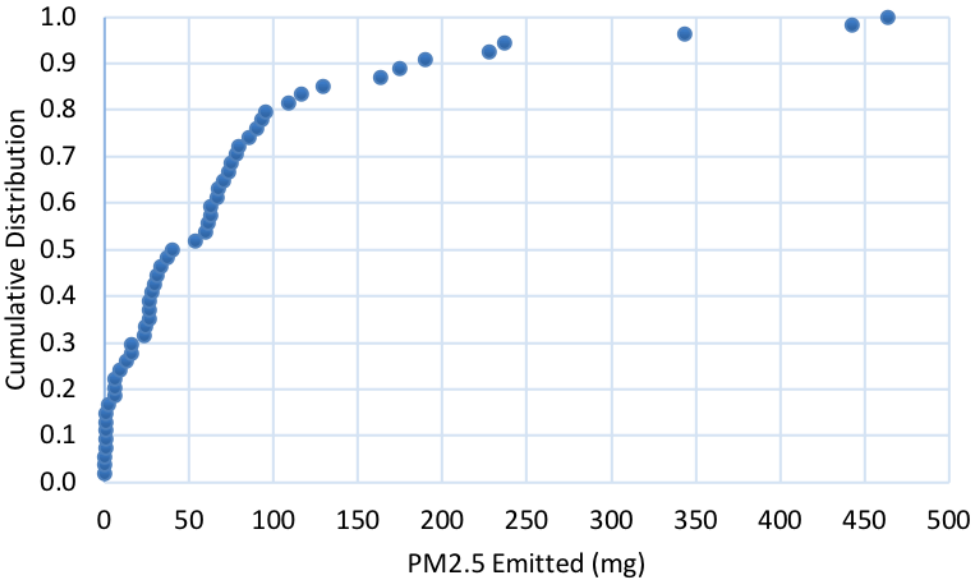

Figure 6. Distribution of $PM_{2.5}$ emissions (mg) per cooking event from literature.

2.3.4 NO_2 Model Parameters

Loss of NO_2 by deposition (k_d), as shown in Equation 1, can have a large impact on modeled concentrations. In a prior study in which Berkeley Lab estimated exposures to NO_2 from natural gas cooking burners, NO_2 first-order deposition rates were modeled as being either 0.5/h or 1.05/h (Logue et al. 2014). These span the range of values between 0.11 and 1.4/h reported in literature for furnished residences (Nazaroff et al. 1993; Spengler et al. 1994; Spicer et al. 1993; Yang et al. 2004). Differences in NO_2 deposition rate can be partly explained by humidity effects and variations in indoor surface characteristics. For the current analysis, we put more emphasis on studies by Zhou et al. (2018) in a single-family NY house, and work by Francisco et al. (2010) and Gordon et al. (2008) in 17 Illinois homes. Those studies both report a central estimate of 0.75/h for the NO_2 deposition rate. In light of these data, we model NO_2 deposition rate using a triangular distribution with mode of 0.75/h, minimum of 0.5/h, and maximum of 1.0/h.

In the prior Berkeley Lab study (Logue et al. 2014), NO_2 penetration factor was assumed to be 1.0 due to the lack of data. Recently, an NO_2 penetration factor of 0.72 (standard deviation = 0.06) was reported for an unoccupied, sparsely furnished apartment in Illinois (Zhao et al. 2019). However, the applicability of that value to single-family residential analysis is questionable, as air entering the apartment may have come through other parts of the apartment building; and the apparent penetration factor includes deposition to indoor surfaces as the air has moved through those indoor spaces. In single-family homes the pathways of outdoor air entry are assumed to be more direct. And even in multifamily, since California requires mechanical ventilation, and many apartments are provided with supply ventilation systems, the pathway of outdoor air entry is likely to be much more direct than in the Illinois building. Due to the lack of any other data (to our knowledge) on NO_2 penetration factor, we assumed a constant value of 1.0 in the modeling described here.

Aggregated $PM_{2.5}$ and NO_2 outdoor data from the Air Quality Monitoring Information System (AQMIS) (California Air Resources Board 2020) was used to provide ambient concentrations of these two pollutants when running the simulations. Hourly outdoor data for NO_2 (ppb) for the years 2016–2018 were downloaded from the AQMIS website. Data was extracted for 15 of the largest counties in California where approximately 83% of the state population reside. Data were obtained for 43 monitoring sites with NO_2 outdoor data. Boxplots were created to show the seasonal trend of NO_2 concentrations averaged between 5:00 pm and 8:59 pm in consideration of the largest amount of cooking most commonly being dinner (Figure 7). Because NO_2 concentrations tend to be higher in the winter months, November to January data were used to characterize the outdoor NO_2 concentrations. Outdoor NO_2 concentrations were approximated using a cropped normal distribution, with mean of 12 ppb, standard deviation of 18 ppb, and minimum and maximum of the simplified distribution corresponding to the 5th and 95th percentiles of the actual distribution, i.e., 3 ppb and 44 ppb.

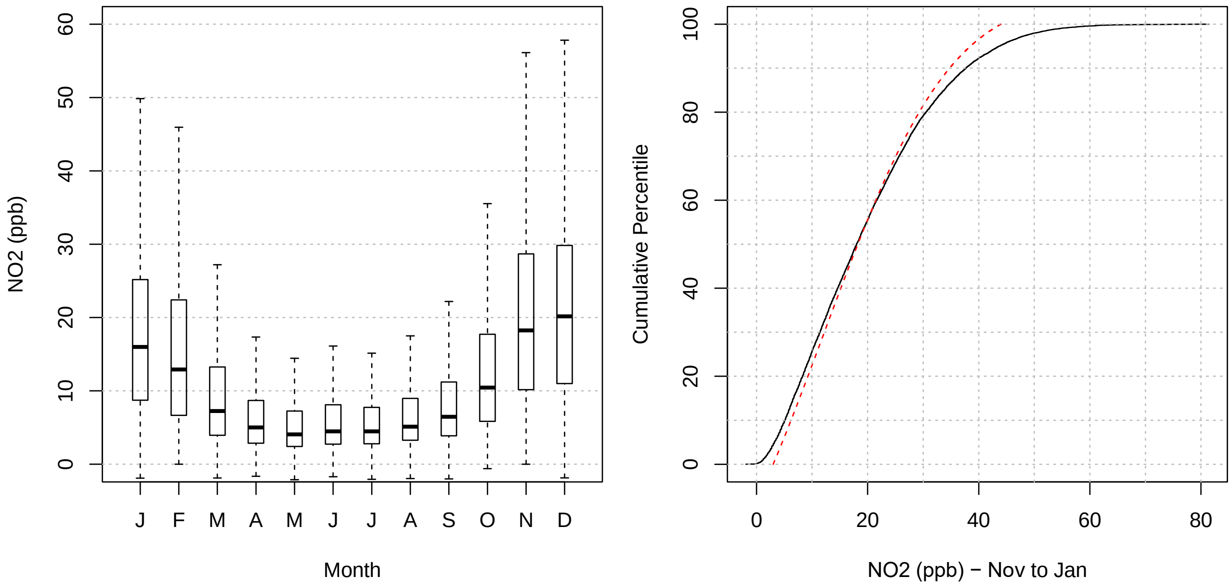

Figure 7. Boxplot showing daily averaged NO_2 (ppb) in the evening between 5:00 and 8:59 pm from 43 sites, plotted by month. The cumulative distribution of NO_2 (ppb) in the winter months is approximated using a cropped normal distribution (red dotted line).

Table 4 Summary of outdoor NO_2 from 43 air monitoring sites

County	Air Quality Monitoring Site Numbers	NO_2 Mean (ppb)	NO_2 Median (ppb)	NO_2 5th–95th Percentile (ppb)
Orange	30177, 30178	27.6	26.8	8.8–47.6
Los Angeles	70088, 70074, 70060, 70591, 70075, 70087, 70090, 70301, 70185, 70112, 70073	24.5	23.5	4.6–47.7
San Bernardino	36203, 36197, 36306, 36175	23.5	23.5	3.2–45.7
Riverside	33137, 33144, 33158, 33165	18.4	16.7	3.4–40.1
San Diego	80128, 80114, 80140, 80136	14.2	12.0	2.3–33.8
Ventura	56434, 56436	11.5	10.5	1.1–26.0
Kern	15248, 15255, 15257	21.6	21.0	6.6–39.3
Fresno	10245, 10251	20.1	17.7	6.1–44.0
San Joaquin	39252	23.1	22.2	8.8–40.7
Sacramento	34295, 34311	10.6	9.0	1.5–23.9
Contra Costa	07442, 07448, 07447	13.3	12.1	2.7–27.0
Alameda	60347, 60344, 60349	19.3	18.8	4.8–36.0
San Mateo	41541	19.5	19.8	3.9–35.3
San Francisco	90306	21.4	20.8	5.9–41.4
Santa Clara	43389	22.9	21.4	5.9–43.0

2.3.5 $PM_{2.5}$ Model Parameters

The $PM_{2.5}$ deposition rate was modeled using a triangular distribution with mode of 0.6/h, minimum of 0.3/h, and maximum of 1.2/h. This is based on results reported by Wallace et al. (2013), who analyzed $PM_{2.5}$ time series in 58 Canadian homes during winter. The measured median AER of the sample was 0.34/h, which is similar to the AER for new California homes that are mechanically ventilated per Title 24. And Canadian homes are expected to have similar $PM_{2.5}$ deposition as California homes owing to the homes being of similar construction and with similar materials and furnishings. Wallace et al. reported median and interquartile deposition rates of 0.60/h and 0.34–1.19/h. These deposition rates are higher than the point estimate of 0.3/h used in a modeling system developed for estimating $PM_{2.5}$ and other pollutants in large populations of US homes (Fazli and Stephens 2018) and lower than the $PM_{2.5}$ deposition rates inferred from size-dependent rates reported for a study of cooking related PM emission events in 14 houses in Australia (He et al. 2005).

We modeled the $PM_{2.5}$ penetration factor as a uniform distribution ranging from 0.4 to 0.6. This range, which is at the lower end of penetration factors reported in the literature, was selected because the exhaust mechanical ventilation systems which are common in new California homes cause outside air to enter through the building envelope, which results in substantial particle removal. A recent study of ventilation and filtration systems that was conducted in a typically airtight (5 air changes per hour at 50 Pascal indoor-outdoor pressure difference), 2006-built home in Sacramento reported estimates of penetration factors of 0.4–0.5 for particles between 0.3 and 2.5 μm when the house used exhaust ventilation (Singer et al. 2016). Long et al. (2001) analyzed time- and size-resolved PM data to estimate a range for penetration factors of 0.2 to 0.9 in 9 homes. Williams et al. (2003) estimated a penetration factor of 0.72 (standard deviation = 0.21) in 37 NC homes. Stephens and Siegel (2012) reported a mean penetration factor of 0.47 (standard deviation = 0.15) from measurements in 18 homes. Zhao and Stephens (in preparation) found a mean penetration factor of 0.80 (standard deviation = 0.09) from measurements in 9 single-family Chicago homes.

For homes having supply or balanced ventilation systems, the penetration factor is closely tied to the efficiency of filtration on the outdoor supply air. In California, new homes are required to use a MERV13 filter for supply ventilation systems. A recent study of new residential filters (Fazli et al. 2019) reported $PM_{2.5}$ removal efficiencies for eight MERV 13 filters: median of 70%, IQR of 63–73%, and range excluding outliners of 45–90%. A penetration factor of 0.4–0.6 is equivalent to having a supply ventilation filter that removes 40–60% of outdoor $PM_{2.5}$ as air is brought into the house, which is within the lower range of the values reported by Fazli et al. (2019).

Distributions of 24-h average outdoor $PM_{2.5}$ ($\mu g/m^3$) were developed from data downloaded from the California Air Resources Board AQMIS website (California Air Resources Board 2020). Three years of data (2016 to 2018) were downloaded for 15 of the largest counties in California, with 35 monitoring sites in populated areas (Table 5). Daily average $PM_{2.5}$ concentrations follow lognormal distributions with GM of 8.9 $\mu g/m^3$ and GSD of 2.1. Values of outdoor $PM_{2.5}$ were cropped to limit values between 3 and 25 $\mu g/m^3$, roughly corresponding to 5th and 95th percentiles of the AQMIS data (Figure 8).

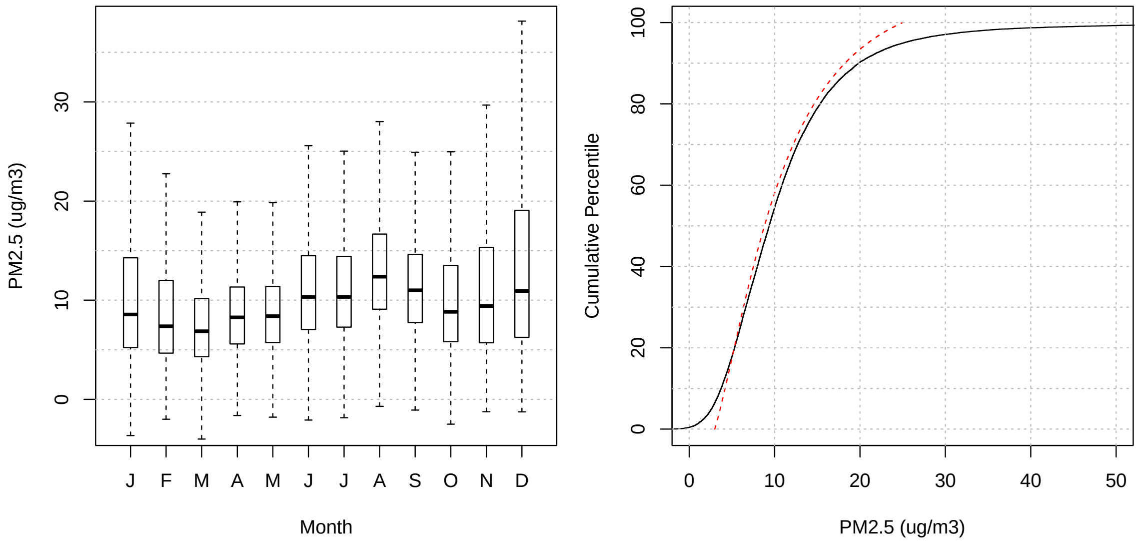

Figure 8. Left panel presents distributions of daily averaged ambient $PM_{2.5}$ ($\mu g/m^3$) from 35 monitoring sites in the 15 most populated counties, by month. Right panel shows the actual cumulative distribution of $PM_{2.5}$ and the simplified distribution (red dotted line).

Table 5 Summary of outdoor $PM_{2.5}$ from 35 air monitoring sites

County	Air Quality Monitoring Site Number	Mean $PM_{2.5}$ (μg/m^3)	Median $PM_{2.5}$ (μg/m^3)	$PM_{2.5}$ 5th–95th Percentile (μg/m^3)
Orange	30178	12.9	11.7	4.6–24.1
Los Angeles	70074, 70084, 70090, 70110, 70301, 70591	12.4	11.2	3.2–25.2
San Bernardino	36175, 36306	12.5	10.4	3.5–27.2
Riverside	33031, 33144, 33158, 33165	12.0	11.0	2.6–24.2
San Diego	80128, 80140	9.9	9.3	2.2–20.1
Ventura	56434, 56435, 56436	8.9	8.2	2.2–17.3
Kern	15255	15.4	11.6	4.0–40.7
Fresno	10248, 10251	14.2	10.7	3.4–38.0
San Joaquin	24531, 39252	12.7	9.4	3.7–32.5
Sacramento	34295, 34310, 34311	10.5	8.0	1.8–25.4
Contra Costa	07447, 07448	10.6	8.5	3.0–20.9
Alameda	60344, 60347, 60349	10.1	7.9	2.8–21.2
San Mateo	41541	9.3	7.9	1.9–18.3
San Francisco	90306	9.7	7.9	1.5–20.4
Santa Clara	43383, 43389	8.3	6.5	1.1–18.4

3. Results

An example of the predicted NO_2 and $PM_{2.5}$ concentrations at various levels of capture efficiency are shown in Figure 9 and Figure 10. This illustrative model run was performed for a 900 ft^2 apartment with an air exchange rate of 0.4/h. Other model parameters, such as NO_2 emission rate, outdoor concentration, and deposition rate were selected from the central estimates as defined in the Methods. The predicted concentrations follow the expected time-series profile, where there is an increase in NO_2 and $PM_{2.5}$ concentration as a result of cooking emissions, followed by a decline in concentration once cooking ended. The predicted 1-hour maximum NO_2 concentration resulting from the reference pasta dinner without range hood use (i.e., CE = 0) for this model run is 144 ppb. With range hood use at 50% capture efficiency, the predicted 1-hour maximum NO_2 concentration is 62 ppb. A higher capture efficiency at 70% lowers the predicted 1-hour maximum NO_2 concentration to 54 ppb. Using a range hood for 10 extra minutes after cooking for this model run would further lower the 1-hour maximum concentration to 39 ppb (CE = 0.5) and 35 ppb (CE = 0.7), respectively.

$PM_{2.5}$ results show three distinct peaks corresponding to breakfast, lunch, and dinner. Because breakfast was modeled to emit more $PM_{2.5}$ (100 mg) than lunch and dinner (50 mg each), the highest $PM_{2.5}$ concentration was predicted following the cooking of breakfast. Similar to the case for NO_2, there is a substantial difference between the predicted $PM_{2.5}$ concentration for cooking with or without using a range hood. The predicted 24-hour average $PM_{2.5}$ concentration without range hood use (i.e., CE = 0) for this illustrative model run is 37 μg/m^3. With range hood use at 50% capture efficiency, the predicted 24-hour average $PM_{2.5}$ concentration is 17 μg/m^3. A higher capture efficiency at 70% lowers the predicted 24-hour average $PM_{2.5}$ concentration to 15 μg/m^3. Using a range hood for 10 extra minutes after cooking for this model run would further lower the 1-hour maximum concentration to 11 μg/m^3 (CE = 0.5) and 10 μg/m^3 (CE = 0.7), respectively.

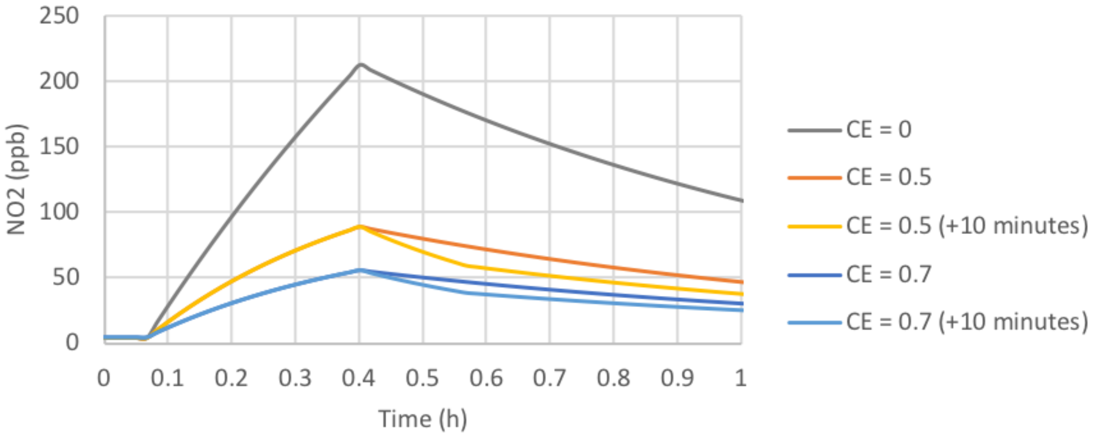

Figure 9. An example of NO_2 simulation runs showing predicted concentrations at 0, 50%, and 70% capture efficiency (CE). Included in the plot are two additional cases to illustrate the effect of continuously operating the range hood for 10 more minutes after cooking.

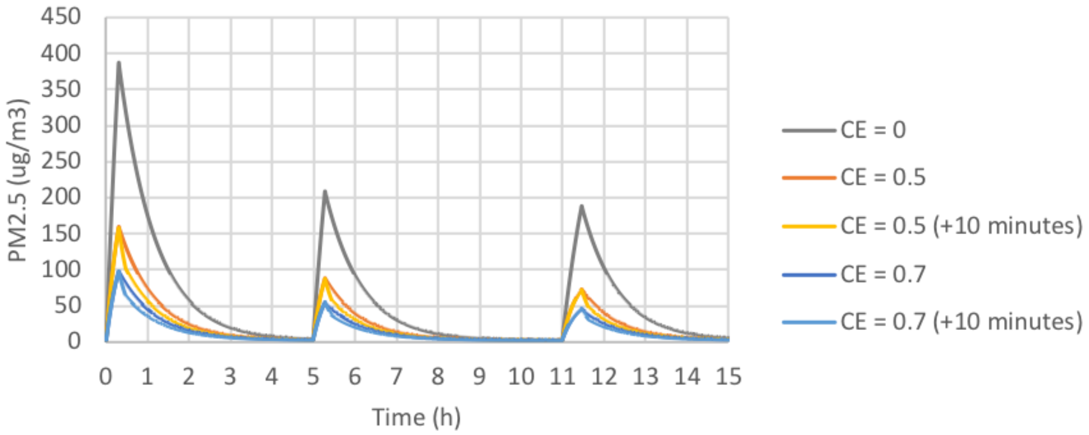

Figure 10. An example of $PM_{2.5}$ simulation runs showing predicted concentrations at 0, 50%, and 70% capture efficiency (CE). Included in the plot are two additional cases to illustrate the effect of continuously operating the range hood for 10 more minutes after cooking.

3.1 NO_2

Summary results of simulations conducted to determine the percent of homes that would have unacceptably high NO_2 from cooking of the reference pasta dinner are presented in Table 6. If no range hood is used, the analysis estimates that approximately one-third (31%) of new California homes will have NO_2 concentrations above the 100 ppb 1h threshold. Single-family attached and multi-family homes are more likely to experience high concentrations of NO_2, relative to single-family detached homes. A capture efficiency of 70% is necessary to reduce the occurrence of homes exceeding the 100-ppb threshold to less than 1%.

Table 6. Fraction of homes that exceed the NO_2 1-h threshold value for varied levels of range hood capture efficiency*.

Capture Efficiency	% Homes Exceeding 100-ppb Maximum 1-hour			
	All	Single-Family Detached	Single-Family Attached	Multi-Family
0	31%	19%	33%	38%
0.50	6%	0.2%	2%	10%
0.55	4%	0.1%	1.2%	7%
0.60	2%	0.03%	0.5%	4%
0.65	1.2%	0%	0.2%	2.2%
0.70	0.5%	0%	0.04%	0.9%
0.75	0.1%	0%	0%	0.2%
0.80	0.01%	0%	0%	0.02%
0.85	0%	0%	0%	0%
0.90	0%	0%	0%	0%

*Modeled range hood airflow = 200 cfm.

Table 6 shows results when the range hood airflow was modeled at 200 cfm. Results change somewhat if the range hood airflow is lower (100 cfm) or higher (300 cfm), as shown in Table 7. Range hood testing by Berkeley Lab has shown that airflows above 150 cfm are required to achieve capture efficiency of 70% (0.7) or higher when using rear cooktop burners. When using front cooktop burners, range hood airflow in the range of 200 to 300 cfm is needed to achieve a capture efficiency of 70% or higher.

Table 7. Effect of airflow and capture efficiency on the fraction of homes that exceed the 1h NO_2 health-based limit when cooking a pasta meal.

Airflow	% Homes Exceeding 100-ppb Maximum 1-hour					
	Capture Efficiency = 0.6		Capture Efficiency = 0.7		Capture Efficiency = 0.8	
	All	Multi-Family	All	Multi-Family	All	Multi-Family
100 cfm	4.1%	7.2%	1.1%	2.0%	0.06%	0.1%
200 cfm	2.4%	4.3%	0.5%	0.9%	0.01%	0.02%
300 cfm	1.2%	2.2%	0.1%	0.2%	0%	0%

Analyses were conducted to assess whether continuing to operate the range hood for 10 extra minutes after cooking would have a meaningful effect on the capture efficiency required to keep homes below the 100 ppb, 1 h NO_2 target. Table 8 shows that the 10 extra minutes of operation has a small impact on the percentage of homes that exceed the 1h threshold value. The occurrence is 0.7% (compared to 2.4% in Table 7) for CE = 0.6 and airflow = 200 cfm, and 0.6% (compared to 1.1% in Table 7) if CE = 0.7 and airflow = 100 cfm. These results indicate that operating the range hood for an additional 10 minutes is insufficient to reduce the performance target to a capture efficiency of 0.6 at 100 cfm, because such a target is expected to result in ~3% of new California homes exceeding the 100 ppb NO_2 standard (Table 9).

Table 8. Effect of airflow and capture efficiency on the fraction of homes that exceed the 1h NO_2 health-based limit when cooking a pasta meal and operating the range hood for 10 minutes after cooking.

Airflow	% Homes Exceeding 100-ppb Maximum 1-hour					
	Capture Efficiency = 0.6		Capture Efficiency = 0.7		Capture Efficiency = 0.8	
	All	Multi-Family	All	Multi-Family	All	Multi-Family
100 cfm	2.7%	4.8%	0.6%	1.0%	0.02%	0.03%
200 cfm	0.7%	1.2%	0.02%	0.04%	0%	0%
300 cfm	0.05%	0.08%	0%	0%	0%	0%

3.2 $PM_{2.5}$

If no range hood is used, we predicted that about one-third (34%) of new California homes would exceed the NAAQS 24h limit of 35 $\mu g/m^3$, and over half (55%) would exceed WHO's 24h guideline value of 25 $\mu g/m^3$ when cooking all three reference meals in a single day. Using a range hood with capture efficiency of 50% (0.5) or higher (at 200 cfm, Table 9) would dramatically reduce the number of homes exceeding the guidelines to 0.03% and 3%, respectively, using NAAQS and WHO limit values. Multi-family homes are expected to exceed the $PM_{2.5}$ guideline more frequently because of their smaller volume, compared to single-family homes. A capture efficiency of 60% (0.6), for example, is expected to provide better protection such that less than 1% (0.8%) of multi-family homes exceed the WHO guideline.

Table 9. Fraction of homes that exceed a 24h $PM_{2.5}$ health-based guideline and effect of range hood capture efficiency*.

Capture Efficiency	% Homes Exceeding 35 μg/m^3 (NAAQS)				% Homes Exceeding 25 μg/m^3 (WHO)			
	All	SF – Detached	SF – Attached	Multi-Family	All	SF – Detached	SF – Attached	Multi-Family
0	34%	1.4%	12%	58%	55%	11%	39%	87%
0.5	0.03%	0%	0%	0.05%	3%	0%	0.3%	6%
0.55	0%	0%	0%	0.01%	1.3%	0%	0.08%	2%
0.6	0%	0%	0%	0%	0.4%	0%	0%	0.8%
0.65	0%	0%	0%	0%	0.08%	0%	0%	0.1%
0.7	0%	0%	0%	0%	0.01%	0%	0%	0.02%
0.75	0%	0%	0%	0%	0%	0%	0%	0%
0.8	0%	0%	0%	0%	0%	0%	0%	0%

*Modeled range hood airflow = 200 cfm.

Table 10 shows results modeled using different range hood airflow rates. If range hood airflow = 100 cfm, then a higher capture efficiency of 0.7 is needed to keep the occurrence of homes exceeding WHO's 25 μg/m^3 guideline at less than 1%.

Table 10. Effect of airflow and capture efficiency on the fraction of homes that exceed a 24h $PM_{2.5}$ health-based guideline when 3 meals are cooked in a day.

Airflow	% Homes Exceeding 25 μg/m^3 (WHO)					
	Capture Efficiency = 0.5		Capture Efficiency = 0.6		Capture Efficiency = 0.7	
	All	Multi-Family	All	Multi-Family	All	Multi-Family
100 cfm	8%	14%	2%	4%	0.2%	0.3%
200 cfm	3%	6%	0.4%	0.8%	0.01%	0.02%
300 cfm	0.8%	1.4%	0.03%	0.05%	0%	0%

Table 11 shows the effect of continuously operating the range hood for an additional 10 minutes after cooking.

Table 11 Effect of airflow and capture efficiency on the fraction of homes that exceed a 24h health-based limit for $PM_{2.5}$ when cooking three meals per day and operating the range hood for 10 minutes after cooking.

Airflow	% Homes Exceeding 25 μg/m^3 (WHO)					
	Capture Efficiency = 0.5		Capture Efficiency = 0.6		Capture Efficiency = 0.7	
	All	Multi-Family	All	Multi-Family	All	Multi-Family
100 cfm	3%	6%	0.4%	0.8%	0%	0.02%
200 cfm	0.05%	0.09%	0%	0%	0%	0%
300 cfm	0%	0%	0%	0%	0%	0%

4. Discussion

This analysis was designed to inform the selection of a minimum capture efficiency that could be included as a requirement in future California statewide buildings standards. The framework was that every dwelling unit should have kitchen exhaust ventilation that, if used appropriately, will almost certainly avoid unacceptable levels of air pollutants from gas burners or cooking. The analysis considered meals that emitted substantial quantities of NO_2 and $PM_{2.5}$, though far from the highest values reported in the technical literature, and air pollutants entering from outdoors. The objective was set to identify a performance level that will result in <1% of new homes having NO_2 or $PM_{2.5}$ from cooking exceed health guidelines. The capture efficiency values recommended in this study can be interpreted as broadly protective but not perfectly protective; they will not guarantee that indoor NO_2 and $PM_{2.5}$ never exceed the health guidelines.

Preliminary analysis of NO_2 and $PM_{2.5}$ measured in four multi-family buildings under Task 2 of this project suggests that currently code-compliant range hoods may not be sufficient to maintain acceptable indoor air quality; though it is not yet known how much of the deficiency can be attributed to occupants choosing to not activate an installed range hood or occupants choosing to cook on front burners (which translates to lower capture efficiency) versus poor equipment performance. The recently completed field study of 70 new single-family California homes (Chan et al. 2019) found almost no cases of 1h NO_2 or weekly average $PM_{2.5}$ exceeding the health guidelines considered here.

Multi-family homes were found to be more dependent on range hood with adequate capture efficiency because of their smaller floor area, compare to single-family homes. Variations in cooking frequency and the quantity of food prepared both across and within building type, were not modeled. Rather, the analysis assumes that the modeled meal(s) with substantial NO_2 and $PM_{2.5}$ emissions can reasonably happen in any new California home, regardless of the dwelling type or size. Given that there is vast variability in cooking-related emissions, and the emission values modeled were not extreme values, using the same emission scenario has the benefit of consistency for this analysis.

There are a number of model assumptions that likely impacted the results. First, the well-mixed assumption is likely not valid for larger single-family homes, especially those that have multiple floors. On the other hand, the well-mixed assumption is much closer to valid for multi-family homes because of their smaller floor area. An alternative approach is to apply a multi-zone model but doing so greatly increases the complexity and uncertainty, because the magnitude of interzonal airflows are highly variable and not well characterized. O'Leary et al. (2019b) assumed that there is no mixing between the kitchen and the rest of the home when modeling kitchen ventilation strategies for the English housing stock. However, that assumption is clearly invalid for the open kitchen layout common among new California homes. Use of a central forced air system commonly present among new California homes will also enable mixing. Considering that multi-family homes are a focus area of this analysis, the well-mixed assumption is a reasonable simplification.

Among the many input parameters that describe the pollutant dynamics of NO_2 and $PM_{2.5}$ indoors, the deposition rates are the most influential and least well characterized in literature. This analysis used a range of values when available to represent some of the differences found in studies of homes with different characteristics.

For simplicity, this analysis did not explicitly model the subtle effects of using different ventilation system (exhaust, supply, or balance) or filtration from the furnace filter on $PM_{2.5}$. For multi-family homes, this model also does not consider the effects of air exchange between units. And the analysis only considered the sources of cooking and pollutants from outdoor air.

When applying these results to set a minimum requirement, it is important to also consider other aspects of range hood performance. Extensive measurements have shown big differences in capture efficiency when cooking occurs on front vs. back cooktop burners; and there is some evidence that front burners are used more commonly.

It is also important to note that the results of a recently developed standard method of test for range hood capture efficiency may not directly translate to the same in-use effectiveness.

5. Conclusions

Model simulations of NO_2 and $PM_{2.5}$ from cooking meal(s) with substantial emissions suggest that a minimum capture efficiency of 60–70% or higher is needed to maintain acceptable indoor pollutant levels for NO_2 and $PM_{2.5}$. Because of their smaller size, multi-family homes are more dependent on having a range hood that can effectively remove NO_2 and $PM_{2.5}$, compared to single-family homes. The analysis determined that a capture efficiency of 70% is required to keep 1h NO_2 levels in almost all homes below 100 ppb when cooking a pasta dinner for 3-4. For $PM_{2.5}$, a capture efficiency of 60% is needed to maintain 24h average concentrations below 25 $\mu g/m^3$ when cooking three meals that emit particles. These results assumed a range hood airflow rate of 200 cfm, which appears to be needed by many currently available range hoods to achieve these levels of CE when cooking occurs on rear cooktop burners. Slightly lower CEs could be acceptable if users could be relied upon to operate the range hood for an extra 10 extra minutes after cooking.

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