# The Effects of Cooking on Residential Indoor Air Quality: A Critical Review of the Literature with an Emphasis on the Use of Natural Gas Appliances

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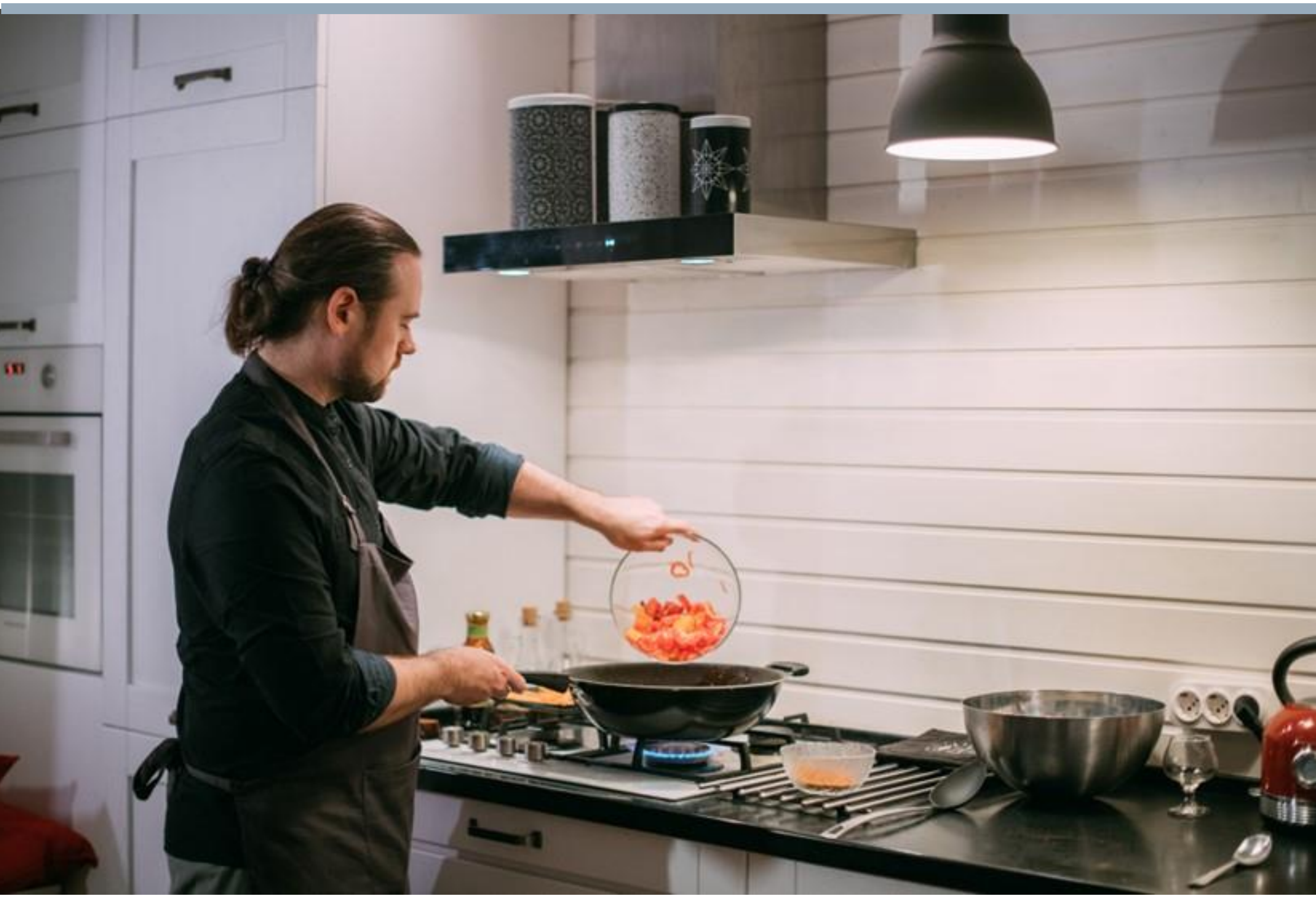

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# Introduction

A variety of heat sources are used for indoor cooking in the United States, including electricity, natural gas, wood, and coal. Indoor burning of wood and coal have been shown to be unhealthful and are the subject of warnings by the US Environmental Protection Agency (USEPA 2022) and the National Cancer Institute (NCI 2022). These cooking fuels are being phased out where they still occur. In most of the country, however, cooking typically relies on cleaner heat sources such as natural gas and electricity and occurs in settings in which care is taken to provide ventilation. In these settings, the air emissions are due to the type of heat source (i.e., electricity and natural gas), the food being cooked, and the method of cooking.

Which of these emission sources is the main driver of health risk? The purpose of this report is to review the published literature relevant to this question, and to evaluate the relative contribution to health impacts from air emissions due to combustion of natural gas, electricity, and the act of cooking. A wide array of studies that support this analysis have been conducted, in both laboratory settings and in kitchen environments. As described in this report, the literature has generally found that indoor air pollution from cooking varies widely across types of food being cooked and, to a lesser extent, the type of fuel being used. A recent review from Abdullah et al. (2013) finds that "it is expected that the use of electricity and gas also contribute to cooking emissions. However, although such emissions will be included in the concentrations reported in the literature, the main contribution to those concentrations is expected to be from compounds deriving from the cooking of the ingredients itself." In other words, when it comes to the indoor air quality of cooking with electricity or natural gas, the health driver is what you are cooking, not the fuel you use to cook it. And the most effective method to protect your health is to provide ventilation during cooking.

# Summary of Findings

Considering the means of heating food during cooking, the air emissions reported in the literature from both electricity and natural gas include airborne releases of particulate matter (PM; UFP, $PM_{2.5}$, and $PM_{10}$), CO, $CO_2$, $NO_x$, and $NO_2$[1]. Depending on the food and whether cooking oils are used, air emissions from cooked food have been shown to generate numerous other airborne chemical releases including polycyclic aromatic hydrocarbons (PAHs), acrylamide, and heterocyclic amines. These latter chemicals are not generated by natural gas combustion as the chemical precursors (proteins, amino acids) are only present in food components such as muscle meat (pork, beef, chicken) and are not present in natural gas. Some of the compounds released from the cooked food include human carcinogens. The health effects from what is being cooked have been shown to be greater than those from the heat source itself. While only a limited number of studies have been conducted using both natural gas and electric cooking appliances to provide a direct comparison, the relative contributions to indoor air quality impacts from these two types of cooking appliances is also evaluated in this report.

This report also considers and discusses various mitigating factors such as ventilation, appliance maintenance, personal food choices, and the need to educate the public on the hazards of cooking food as well as methods for mitigating impacts on indoor air quality.

As discussed in this report, there are several significant misconceptions regarding the impacts on indoor air quality associated with natural gas cooking appliances that undermine realistic and economically feasible decision-making aimed towards protecting human health. In some cases, we find that media reports of the

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[1] UFP, ultrafine particles; $PM_{2.5}$, particulate matter ≤2.5-micron diameter; $PM_{10}$, particulate matter ≤10-micron diameter; CO, carbon monoxide; $CO_2$, carbon dioxide; $NO_x$, non-specific nitrogen oxides; $NO_2$, nitrogen dioxide.

results of published studies misrepresent the import of any findings and conflate the greenhouse gas compounds emitted during cooking with potential health effects on indoor air quality. The two are not the same thing.

In this report, we focus on potential health effects, and identify four major issues and three other issues that are highlighted by the literature review. The three other issues are tabulated at the end of this report. The four major issues are as follows:

**Issue 1:** There has been recent, extensive media coverage, similar to this from CBS news on January 10, 2023[2]: "A December study found that 13% of childhood asthma cases nationwide can be blamed on indoor use of gas stoves. A previous study from a decade ago found that a gas stove at home increased a child's risk of asthma by 42%." These recent news reports are based on studies published by Gruenwald et al. (2023) and Lin et al. (2013), respectively. The Gruenwald et al. study, however, calculated the 13% value by combining data from North America and Europe. However, the data demonstrate that in North America there is not a statistically significant risk of asthma. Moreover, the data shows that in none of the regions studied was there a statistically significant relationship between $NO_2$ (which comes from combustion of natural gas) and asthma. Therefore, Gruenwald et al.'s data indicate that any effects may be due to the foods being cooked (or other confounding factors) rather than the fuel used – there is no other distinguishing factor of gas cooking appliances, as opposed to electric cooking appliances, for which an association with childhood asthma has been suggested. In contrast to Gruenwald et al. and Lin et al., Phase 3 of the International Study of Asthma and Allergies in Childhood (ISAAC) found that for a cohort of 512,707 primary and secondary school children from 47 countries there was "no evidence of an association between the use of gas as a cooking fuel and either asthma symptoms or asthma diagnosis." ISAAC is historically the largest collaborative worldwide epidemiologic project focused on the possible association between gas stove use and asthma ever undertaken. As this shows, there is a mismatch between the actual underlying data, flawed study results and media reports, and public policy.

**Issue 2:** The air emissions from cooking food has been reported to impact residential indoor air quality. The extent to which indoor air quality is impacted is highly dependent on the types of food being cooked and the cooking conditions such as time, temperature, space configuration, and ventilation. It is far less dependent on the heat source for the cooking, either natural gas or electricity.

**Issue 3:** The type of appliance (natural gas or electric) used to cook food indoors is not a significant determinant of residential indoor air quality. While CO and $NO_x$ emissions and post-combustion formation of $NO_2$ are unique to gas ranges due to the combustion of natural gas, their concentrations in residential indoor air do not pose a health risk. Likewise, the trace elements in unburned natural gas have not been demonstrated to be at concentrations that would pose human health risk.

**Issue 4:** To date, there has not been a comprehensive human health risk assessment conducted to evaluate potential indoor air impacts to human health associated with the process of cooking. Nearly all studies published on the impacts of cooking on indoor air quality have focused on emissions and resulting concentrations of various chemical constituents, rather than any demonstrated human health risk.

The technical basis for each major issue, as well as the three other issues, is described in the next sections. When reference is made to ambient air quality standards (AAQS) for $PM_{2.5}$, $PM_{10}$, CO, and $NO_2$, the values referred to will be either the federal Primary National Ambient Air Quality Standards (NAAQS) and/or the

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[2] https://www.cbsnews.com/news/gas-stove-ban-federal-regulators-consumer-product-safety-commission-richard-trumka/

California Ambient Air Quality Standards (CAAQS) per California Air Resources Board (CARB) guidelines[3]. The AAQS are summarized below in Table 1.

It is important to understand that while AAQS can perhaps provide a reference point, they are not applicable to the evaluation of indoor air quality and associated health-based impacts. AAQS as referred to in this report are merely being used as points of reference and do not indicate adverse health effects. In addition, the AAQS are presented over various averaging times: 1-hour, 8-hour, 24-hour, and annual. Some studies compare peak measured values to these time-averaged values, which is clearly incorrect. Note that concentrations of air emissions presented throughout this report are presented in the units (ppb or µg/m$^3$) in which they are reported in each respective study.

**Table 1. Ambient Air Quality Standards[4]**

| Constituent | 1-Hour Average | 8-Hour Average | 24-Hour Average | Annual Average |
|---|---|---|---|---|
| $PM_{2.5}$ (µg/m$^3$) | -- | -- | 35 (US) | 12 (CA)<br>12 (US) |
| $PM_{10}$ (µg/m$^3$) | -- | -- | 50 (CA)<br>150 (US) | 20 (CA) |
| CO (ppm) | 20 (CA)<br>35 (US) | 9 (CA)<br>9 (US) | -- | -- |
| $NO_2$ (ppb) | 180 (CA)<br>100 (US) | -- | -- | 30 (CA)<br>53 (US) |

US, National Ambient Air Quality Standard
CA, California Ambient Air Quality Standard

This literature review is timely as states and communities are considering phasing out natural gas stoves. The studies that are being used to support decision making, however, are flawed in ways large and small, as will be discussed in more detail in Issue 1 below.

[3] CARB states, "California law continues to mandate CAAQS, although attainment of the NAAQS has precedence over attainment of the CAAQS due to federal penalties for failure to meet federal attainment deadlines." https://ww2.arb.ca.gov/resources/california-ambient-air-quality-standards

[4] Concentration units for PM (µg/m$^3$), CO (ppm), and $NO_2$ (ppb) are reported as such by historical convention, but can be converted by the following equation: µg/m$^3$ = ppb*(12.187)*(M)/(273.15 + °C) where M is molecular weight and °C is 25°C.

# Major Issues

**Issue 1: There has been recent, extensive media coverage, similar to this from CBS news on January 10, 2023[5]: "A December study found that 13% of childhood asthma cases nationwide can be blamed on indoor use of gas stoves. A previous study from a decade ago found that a gas stove at home increased a child's risk of asthma by 42%." These recent news reports are based on studies published by Gruenwald et al. (2023) and Lin et al. (2013), respectively. The Gruenwald et al. study, however, calculated the 13% value by combining data from North America and Europe. However, the data demonstrate that in North America there is not a statistically significant risk of asthma. Moreover, the data shows that in none of the regions studied was there a statistically significant relationship between $NO_2$ (which comes from combustion of natural gas) and asthma. Therefore, Gruenwald et al.'s data indicate that any effects may be due to the foods being cooked (or other confounding factors) rather than the fuel used – there is no other distinguishing factor of gas cooking appliances, as opposed to electric cooking appliances, for which an association with childhood asthma has been suggested. In contrast to Gruenwald et al. and Lin et al., Phase 3 of the International Study of Asthma and Allergies in Childhood (ISAAC) found that for a cohort of 512,707 primary and secondary school children from 47 countries there was "no evidence of an association between the use of gas as a cooking fuel and either asthma symptoms or asthma diagnosis." ISAAC is historically the largest collaborative worldwide epidemiologic project focused on the possible association between gas stove use and asthma ever undertaken. As this shows, there is a mismatch between the actual underlying data, flawed study results and media reports, and public policy.**

Gruenwald et al. (2023) relied entirely on odds ratio (OR) results for asthma and wheeze as reported by Lin et al. 2013 to calculate a population attributable fraction (PAF). Odds ratios are indicators of potential risk whereby an OR value exceeding 1 may indicate a potential increased risk and an OR less than or equal to one indicates the absence of increased risk. The 95% confidence intervals around the OR are critically important as the 95% lower confidence limit is an indication of statistical significance whereby a 95% lower confidence limit less than or equal to one indicates the absence of a statistically significant relationship. A PAF calculation is only appropriate where an odds ratio (or relative risk) represents a statistically significant association, and it uses various inputs to then determine the portion of the population affected by the statistically significant association as indicated by the OR. In fact, as discussed in Rockhill et al. (1998), use of the PAF requires not only a statistically significant relationship, it also requires a causal relationship, which is much more difficult to establish definitively. As they state: "The assumptions underlying valid population attributable fraction estimation include the following: a causal relationship between the risk factors and disease…". None of the studies attempting to associate gas stove use to asthma have demonstrated a causal association. Gruenwald et al. (2003) state, "We quantified the population attributable fraction (PAF) for gas stove use and current childhood asthma in the US. Effect sizes previously reported by meta-analyses for current asthma (Odds Ratio = 1.34, 95% Confidence Interval (CI) = 1.12–1.57) were utilized in the PAF estimations." Gruenwald et al. further state, "Full manuscripts (n = 27) were independently reviewed by coauthors; none reported new associations between gas stove use and childhood asthma specifically in North America or Europe. As a result, effect sizes previously reported for current asthma in North America and Europe combined (weighted by inverse variance; N studies = 10; Odds Ratio (OR) = 1.34, 95% Confidence Interval (CI) = 1.12–1.57) were utilized in the PAF estimations [1]. The combined effect size was based on a North America specific effect size (N studies = 3; OR = 1.36, 95% CI = 0.76–2.43) and Europe-specific effect size (N studies = 7; OR = 1.34, 95% CI = 1.13–1.60), as reported in a previously published meta-analysis [1]. We combined effect sizes for North America and Europe

[5] https://www.cbsnews.com/news/gas-stove-ban-federal-regulators-consumer-product-safety-commission-richard-trumka/

given the similarities in housing characteristics and gas-stove usage patterns across these geographies." Note [1] in the previous sentence is in reference to Lin et al. (2013).

The Gruenwald et al. approach of combining the Lin et al. current asthma OR results for North America and Europe is flawed. They did so because of "similarities in housing characteristics and gas-stove usage patterns across these geographies" but provided no reference study or report to substantiate this assertion. In fact, as discussed below, while the gas stove use and current asthma OR for Europe is statistically significant (OR = 1.34, 95% CI = 1.13–1.60), the gas stove use and current asthma OR for North America is not statistically significant (OR = 1.36, 95% CI = 0.76–2.43) as reported in both Lin et al. and Gruenwald et al. Therefore, there are clearly differences between the two geographies and combining data from the two geographies is not appropriate and contradicts Gruenwald et al.'s fundamental assumption that they are similar.

Now, let's take a closer look at the Lin et al. (2013) study upon which Gruenwald et al. (2023) is based. Lin et al. conducted a meta-analysis of 41 individual epidemiological studies of residential gas stove use and childhood asthma and wheeze as health outcomes whereby all individual studies reported ORs and confidence intervals for gas stove use and health outcomes and in some cases $NO_2$ exposure and health outcomes. The original 41 studies were classified by study population as Asia, Europe, or North America. The meta-analysis was conducted on all three populations combined as well as individually. We note that Lin et al. (2013) found no statistically significant association between gas stove use and wheeze for children in Asia, Europe, or North America. The results discussed below are focused on gas stove cooking and asthma because Lin et al. concluded that indoor air $NO_2$ while cooking was not associated with current, lifetime, or all asthma and because childhood asthma is the critical health outcome associated with $NO_2$ exposure.

The Lin meta-analysis results found that for all three populations combined gas cooking was significantly associated with current asthma (OR=1.49, 95% CI= 1.28-1.73), lifetime asthma (OR=1.29, 95% CI= 1.09-1.52), and all asthma (OR=1.37, 95% CI= 1.22-1.53). In contrast, for all three populations combined exposure to $NO_2$ was **not** significantly associated with current asthma (OR=1.36, 95% CI= 0.57-3.29), lifetime asthma (OR=1.08, 95% CI= 0.95-1.23), or all asthma (OR=1.09, 95% CI= 0.91-1.31). Therefore, the reported statistically significant association between gas stoves and asthma does not appear to be due to $NO_2$ – indicating that there may not be any association between $NO_2$ releases from gas stoves during cooking and asthma. Instead other associated factors such as smoking, age and size of housing, cooking habits, or socioeconomic status, may account for the reported association.

Importantly, when the meta-analysis was stratified by study population, gas cooking in North America was not significantly associated with current asthma (OR=1.36, 95% CI= 0.76-2.43), lifetime asthma (OR=0.86, 95% CI= 0.60-1.24), or all asthma (OR=1.12, 95% CI= 0.73-1.73). Thus, when we consider only North America, Lin et al. found that gas stove cooking is not associated with current, lifetime, or all asthma. Note that since $NO_2$ exposure was not associated with asthma for the combined populations, Lin et al. did not stratify the $NO_2$ meta-analysis by Asia, Europe, or North America.

To add to these mismatches between what the study shows and what is reported, the Gruenwald et al. PAF calculation is further flawed by the fact that the 2019 American Housing Survey (AHS) gas fuel use data for the U.S. on which it relies is based on data from just 9 of 50 U.S. states. In other words, the entire PAF analysis is based on percent representation of U.S. states of only 18%. Furthermore, the mean PAFs for these 9 states as calculated by Gruenwald et al. and shown in Gruenwald et al. Figure 4, ranged from just 3% to as high as 21.1%. This very large range of mean PAFs in combination with only 18% representation for the entire U.S. raises serious concerns regarding interpretation of these apparently flawed findings.

Clearly, the difference in OR results for Europe and North America as reported by Lin et al. are exactly the opposite of what Gruenwald et al. has claimed (that gas stove usage in Europe is similar to that in North America). The absence of a statistically significant association between gas stove use and either current asthma or wheeze in the North American population compared to Europe and Asia is an obvious indication of the more stringent and state-of-the-art building, appliance, and ventilation standards in North America as compared to Europe and Asia. As noted above, the PAF analysis reported by Gruenwald et al., which in turn is based on Lin et al., is clearly flawed given that (1) Lin et al. found no association between gas stove use and childhood asthma in North America; (2) because of this, combining the OR data for Europe and North America was inappropriate; and (3) the wide range of mean PAFs that were calculated indicates substantial variability that cannot be used to represent the entire U.S., especially when only 18% of the states are accounted for.

In the Lin et al. study, the analysis of the relationship between gas stoves and asthma did not evaluate other factors such as use of ventilation or exposure to other pollutants released during cooking. In fact, most of the studies included in the meta-analysis did not assess exposures before health outcomes were ascertained, and many did not account for smoking in the home. The Lin et al. study also had conflicting findings because it (along with later reports) found no association between $NO_2$ concentrations and increased incidence of asthma, demonstrating that at the least more study is warranted on this issue of a lack of association between natural gas combustion (one source of $NO_2$) and increased incidence of asthma.

The Lin et al. meta-analysis relied in part on a Russian study by Spengler et al. (2004), who note: “Russian housing is characterized by large, concrete high-rise structures. Apartments are similar in layout and size and are served by district hot water for heating and gas for cooking; mechanical ventilation and air conditioning is a rarity.” This is important because for their meta-analysis of 19 studies on the association between gas stove use and asthma, the Spengler et al. study reported the highest OR of 2.28 for current asthma is likely the driver in the meta-analysis, but is specific to the distinct conditions in Russia. Moreover, the vast majority (14) of the 19 studies did not report statistically significant ORs great than 1 (e.g., no association between gas stove use and asthma). As such, the findings of Lin et al. and Spengler et al. are not applicable to gas stove use for cooking in the U.S. or California.

In contrast to the Lin et al. (2013) study, as reported by Wong et al. (2013), Phase 3 of the International Study of Asthma and Allergies in Childhood (ISAAC) found that for a cohort of 512,707 primary and secondary school children from 47 countries there was “no evidence of an association between the use of gas as a cooking fuel and either asthma symptoms or asthma diagnosis.” ISAAC is historically the largest collaborative worldwide epidemiologic project focused on the possible association between gas stove use and asthma ever undertaken.

There is another consideration in Gruenwald et al.’s study that points to factors other than natural gas combustion as the source of asthma in his data sources. They note: “Nonetheless, our results align with a cross-sectional study which found that the use of a gas stove or oven for heat was a main risk factor for doctor-diagnosed asthma in US children under age six [6].” Reference [6] is a study by Lanphear et al. (2001) who concluded that “Risk factors for doctor-diagnosed asthma included a family history of atopy (odds ratio [OR]: 2.2; 95% confidence interval [CI]: 1.5, 3.1), child's history of allergy to a pet (OR: 24.2; 95% CI: 8.4, 69.5), exposure to environmental tobacco smoke (OR: 1.8; 95% CI: 1.2-2.6), use of a gas stove or oven for heat (OR: 1.8; 95% CI: 1.02-3.2), and presence of a dog in the household (OR: 1.6; 95% CI: 1.1, 2.3).” With a 95% lower confidence limit of 1.0 (correctly rounded from 1.02), the association between “use of a gas stove or oven for heat (OR: 1.8; 95% CI: 1.02-3.2)” is not statistically significant, and therefore, there is no association between gas stove and oven use and asthma. Also, note the extremely high OR and confidence interval for child's history of allergy to a pet (OR: 24.2; 95% CI: 8.4, 69.5), as reported by Lanphear et al. Clearly, child’s history of allergy to a pet is the most important risk factor identified in this study.

**Issue 2: The air emissions from cooking food has been reported to impact residential indoor air quality. The extent to which indoor air quality is impacted is highly dependent on the types of food being cooked and the cooking conditions such as time, temperature, space configuration, and ventilation. It is far less dependent on the heat source for the cooking, either natural gas or electricity.**

Numerous other studies have been published that report on the indoor air quality impacts associated with the cooking of food using both natural gas and electric cooking appliances (e.g., Abdullahi et al. 2013; Buonanno et al. 2009; Dennekamp et al. 2001; Dobbin et al. 2018; Fortmann et al. 2001; Hu et al. 2012; Li et al. 2003; O'Leary et al. 2019; See and Balasubramanian 2006, 2008; Singer et al. 2017; Zhang et al. 2010; Zhao et al. 2010).

Collectively, these studies confirm that a wide range of chemical emissions are produced during the cooking of food indoors, including PM, CO, $CO_2$, $NO_x$, PAHs, acrylamide, and heterocyclic amines. A smaller set of chemicals: CO, $CO_2$, and $NO_x$, are produced during the combustion of natural gas during the cooking process and typically are not released by food during cooking. $NO_2$, however, is a by-product of natural gas combustion, formed by the high temperature oxidation of atmospheric nitrogen ($N_2$) into nitric oxide (NO) and then $NO_2$, and there are other sources of background $NO_2$ including tobacco smoke, car exhaust, etc. PM has been shown to be released from food during cooking, especially at high temperatures, but is also released to a much lesser extent from the combustion of natural gas during cooking as well as from electric stove coils.

The literature is clear that there are many factors that influence the nature and extent of chemical emissions during the cooking of food including the type of food, the oils used in cooking, cooking temperatures and temperature gradients, cooking time, the type of stove, and ventilation configurations and flow rates. This section provides a summary of relevant literature on this issue, which, as can be seen below, has varying data and conclusions that point primarily to the act of cooking itself as the main factor in emissions.

In their review of emissions and indoor air concentrations of PM and chemical composition of PM associated with cooking, Abdullahi et al. (2013) reported on the concentrations of numerous chemicals and elements in cooking smoke and fumes including metals, PAHs, and wide range of other chemicals including inorganic and organic ions, n-alkanes, n-alkanoic acids, n-alkenoic acids, dicarboxylic acids, aldehydes, ketones, lactones, and others. The authors concluded that, "The composition of cooking aerosol is highly diverse, depending upon factors such as the raw food composition, cooking oil (if used), cooking temperature and cooking style." Specifically, emissions of PM and associated chemicals nearly always increased with increased temperature and were higher for cooking of fatty foods, cooking with oils, and frying cook methods as compared to boiling and steaming. While Abdullahi et al. (2013) did not consider effects of stove type or ventilation in their review, the chemical-specific information provided by these authors is among the most comprehensive summary of the very broad range of chemicals released during the process of cooking.

Dobbin et al. (2018) conducted controlled cooking studies in two identical research homes in Ottawa, Ontario. Each test home was equipped with 30-inch wide four burner natural gas stoves in the kitchens. The focus of the study was to evaluate UFP, $PM_{2.5}$, $NO_2$, and NO emissions during and after cooking activities through continuous monitoring using three different exhaust fan configurations. In total, 60 identical 3-hour cooking tests were conducted whereby the first stage was boiling broccoli on a back burner for 5 minutes, and the second stage was frying four hamburger patties on a front burner for a total of 10 minutes. For half the tests, the ventilation fan was turned off when cooking was completed, and, for the remaining tests, the ventilation fan was left on for another 15 minutes after cooking was completed. For all tests monitoring continued after cooking was completed through the remainder of the 3-hour test. Five replicate tests were conducted for each of six ventilation scenarios, which included six different fan speeds and three exhaust fan configurations. Exhaust fan speeds ranged from 76 to 309 cubic feet per minute (CFM). Exhaust fan A had a depth of 18 inches and exhaust fans B and C had depths of 20 inches; in contrast, the depths of the test stoves were both 25 inches. All three exhaust fans were 30-inches wide and mounted under-cabinet.

The maximum peak concentrations measured for $NO_2$ during all cooking tests was 15 ppb, which is well below the more stringent 1-hour average National AAQS of 100 ppb for $NO_2$[6]. For $PM_{2.5}$, the maximum peak concentration measured during all cooking tests was approximately 80 µg/m[33]. In all six ventilation scenarios, 1-hour average $PM_{2.5}$ concentrations integrated over the entire 30 minutes that exhaust fans were running (15 minutes cooking and 15 minutes post-cooking) were well below the 24-hour average AAQS of 35 µg/m$^3$. As is perhaps apparent, these <u>one-hour average</u> concentrations should not be compared directly to a 24-hour time-averaged standard and cannot form the basis for conclusions as to whether that standard was exceeded.

In general, the study found that leaving the fan on after cooking is complete can compensate for low ventilation flow rates. The authors concluded that exhaust fan air flow rates and exhaust duct configuration were the most important factors reducing emissions concentrations following cooking. It is noted that current Title 24 California building code (CEC 2022) requires a minimum of 300 CFM exhaust ventilation for range hoods in enclosed residential kitchens. The two Dobbin et al. $PM_{2.5}$ tests that have peak concentrations exceeding the AAQS for $PM_{2.5}$ would not be considered to be in compliance with California building code.

In the Dennekamp et al. (2001) study, experiments were conducted in a small, sealed laboratory room (70 m$^3$ volume) without ventilation in Aberdeen, Scotland. Both electric and gas appliances were tested with and without food cooking with a focus on the generation of $NO_x$ and UFPs. The experiments using gas and electric ranges were identical, using one ring, four rings, and grill without cooking, all at full power for 15 minutes (min), and separate cooking experiments of boiling water (stove top ring, 15 min, full power), vegetable stir fry (stove top ring, 5 min, full power), bacon fry (stove top ring, 7 min, full power), cake bake (oven, 40 min, 180°C), meat roast (oven, 75 min, 180°C), baked potatoes (oven, 75 min , 180°C), grilled toast (grill, 5 min, full power), and grilled bacon (grill, 10 min, full power). The number of tests performed for each experiment ranged from 2 to 6.

Results showed that $NO_x$ were not detected above baseline[7] for electric range, but were detected above baseline for the gas range, with a maximum concentration of 996 ppb $NO_2$ when all four rings were on full power for 15 min. While this concentration exceeds the more stringent 1-hour average National AAQS of 100 ppb for $NO_2$, as noted above, that standard is for time-averaged measurements, and in addition, these experiments were all conducted in a sealed room without ventilation – making them unrealistic of real-world conditions. California's Title 24 Building Energy Efficiency Standards require that enclosed kitchens be equipped with exhaust ventilation providing at least 5 air changes per hour (ACH). With ventilation that reflected a more realistic, real-world scenario, the measured maximum $NO_2$ concentration of 996 ppb would be significantly reduced, likely below 100 ppb.

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[6] It is not scientifically accurate to compare peak concentrations to regulatory standards that average emissions over longer time periods, including 1, 8, and 24 hours, or a year. In this report we are careful to distinguish whether the test result was a peak or time-averaged concentration, but a peak concentration cannot fairly be asserted to "exceed" a time-averaged regulatory standard, and thus references to such standards are merely intended as points of comparison.

[7] In this study, "Baseline concentrations were calculated by taking the average concentration of eight measurements; four just before the start of the cooking experiment and four after the experiment when the rise in particles or $NO_X$ had gone back to a steady level."

In the case of UFPs, the authors concluded that, "many UFPs are produced not only by gas combustion but also from heating electric plates and grills. Cooking with electricity or gas has the potential to add to particle numbers, mainly through frying and grilling of fatty foods and through the use of fats for frying."

Aside from the authors' claims as noted above, quantitative results are somewhat inconsistent. For example, UFP concentrations are over three-fold higher for one ring electric burner without food cooking (94,000 UFP/$cm^3$) as compared to the one ring gas burner (26,000 UFP/$cm^3$). In contrast, UFP concentrations are slightly higher for four ring gas burner without food cooking (146,000 UFP/$cm^3$) as compared to four ring electric burner (111,000 UFP/$cm^3$). As another example, for gas and electric grills without food cooking, the gas grill generated slightly higher UFP (103,000 UFP/$cm^3$) as compared to the electric grill (77,000 UFP/$cm^3$). In contrast, for gas and electric grills while cooking bacon, the electric grill generated slightly higher UFP (530,000 UFP/$cm^3$) as compared to the gas grill (413,000 UFP/$cm^3$). These overlapping results indicate significant variability due to the large number of uncontrollable factors including differences in stove/oven temperature gradients, heterogeneity in foods, and sealed laboratory room air flows.

The authors reported two statistically significant findings as follows: "UFPs generated by frying bacon on gas was significantly higher than frying vegetables on gas (p=0.006). Frying bacon on gas also resulted in a significantly higher peak concentration of UFPs than frying bacon on an electric ring (p=0.006)." UFP emissions from natural gas burners and electric burners without cooking were not consistently different from one another: therefore, this latter finding of significantly higher UFP emissions from gas stove bacon frying as compared to electric stove bacon frying suggests that cooking method may be an important factor. As discussed in more detail below, there are some indicators that differences in gas stove and electric stove temperature gradients may explain some differences in chemicals formed and released during otherwise identical cooking of foods on gas and electric stoves.

Although the relatively small sample sizes ranging from 2 to 6 samples for each experiment reduces the overall confidence in the study results, this study clearly shows that UFPs are generated by both electric and gas cooking appliances with and without food cooking, and that UFP concentrations tend to be higher with food cooking, especially for fried and grilled meats. However, the study was conducted without any ventilation of food cooking emissions and therefore the "impacts" to indoor air quality are not relevant to residential homes in California due to strict building code requirements that would largely mitigate indoor air concentrations of UFP and other chemicals related to the cooking of food.

A recent study from Stanford University measured methane and $NO_x$ concentrations emitted from natural gas stoves without cooking of food in sealed kitchens without ventilation (Lebel et al., 2022a). Although actual California residential kitchens with existing gas stoves were used in the study, a smaller space within each kitchen and containing the gas stove was enclosed and sealed with plastic sheeting. Exhaust ventilation was not used in any of the tests. These do not represent realistic conditions or potential exposures for typical California kitchens. Measurements within the sealed space were taken over the course of 2 to 3 minutes with the stove top burners turned on and ignited. The stated purpose of the study was to improve estimates of GHG emissions from gas stoves, not health effects. The authors only provided one health-based observation: "Our data suggest that families who don't use their range hoods or who have poor ventilation can surpass the 1-hour national standard of $NO_2$ (100 ppb) within a few minutes of stove usage, particularly in smaller kitchens." The comparison of these 2 to 3-minute $NO_x$ measurements collected from a smaller-than-normal sealed kitchen space without ventilation to a 1-hour average standard is highly misleading and unrealistic. First, as discussed previously, current Title 24 California building code (CEC 2022) requires a minimum of 300 CFM exhaust ventilation for range hoods in enclosed residential kitchens. The Stanford study did not account for any ventilation. Second, the $NO_x$ concentrations measured were essentially maximum or peak concentrations. These cannot be compared to a 1-hour average standard. Realistically, concentrations based on 3-min burner operation and then averaged over a 1-hour period would be much lower than the maximum peak concentration. With ventilation also taken into account, $NO_x$ concentrations would most likely be much lower than the 1-hour average AAQS for $NO_2$.

Under contract to the California Air Resources Board (CARB), Fortmann et al. (2001) conducted a semi-controlled study using a small (824 $ft^2$) ranch style house located in Rohnert Park, California as the field test house. Range exhaust was vented to the outside. Although the test house was not sealed per se, neither heating nor air conditioning were used during the field tests. Samples were collected from the kitchen, living room, and master bedroom. A total of 32 tests were conducted: 7 tests using the electric range, 3 tests using a microwave oven, and 22 tests using the gas range. While results indicated higher CO, $NO_2$, $PM_{2.5}$, and $PM_{10}$ concentrations for many of the gas range cooking scenarios evaluated as compared to electric range cooking scenarios, those concentrations were still within reference ambient air health-based standards, and moreover, this was not always the case. For example, for the frying tortillas scenario, $PM_{2.5}$ concentrations in the kitchen were 566 $\mu g/m^3$ for the gas range and over twice as high (1,269 $\mu g/m^3$) for the electric range. Similarly, for the baking lasagna scenario, $PM_{2.5}$ concentrations in the kitchen were 362 $\mu g/m^3$ for the gas range and three times as high (1,090 $\mu g/m^3$) for the electric range. For the stove top stir fry scenario, $PM_{10}$ concentrations in the kitchen were 774 $\mu g/m^3$ for the gas range and 1,171 $\mu g/m^3$ for the electric range. Consistent with Dennekamp et al. (2001), the fact that neither use of the gas range nor use of the electric range consistently resulted in higher or lower PM concentrations strongly suggests that many factors are involved, not just the type of range being used.

The authors concluded that, "The data indicate that cooking is a significant, although highly variable, source of PM indoors. Exposure to PM due to cooking may be substantial for many individuals, depending on the amount of cooking and the duration of time spent in the home following cooking. With a gas range, exposure to CO and $NO_2$ is increased substantially." The results of the study cannot be used to precisely assess the impact of different types of cooking methods, different foods, or other parameters related to cooking methods and utensils due to the high variability in the emissions. To evaluate the impact of these parameters, a much larger number of tests would need to be performed.

Dobbin et al. (2018), Dennekamp et al. (2001), and Fortmann et al. (2001) all concluded that cooking food can result in substantial impacts to indoor air quality, but none of the studies provided consistent results sufficient for quantitatively characterizing the many factors that influence food cooking emissions such as stove type (gas or electric), cooking temperature gradients, food types, and ventilation.

Li et al. (2003) conducted a study that measured the concentrations of airborne polynuclear aromatic hydrocarbons (PAHs) generated from cooking food and released through restaurant stacks to outdoor air. The emissions were primarily from the food itself being cooked. The specific PAHs emitted from the food were: acenaphthene, acenaphthylene, anthracene, benz(a)anthracene, benzo(a)pyrene, benzo(b)chrycene, benzo(b)fluoranthene, benzo(e)pyrene, benzo(ghi)perylene, benzo(k)fluoranthene, chrysene, coronene, cyclopenta(c,d)pyrene, dibenzo(a,h)anthracene, fluoranthene, fluorene, indeno(1,2,3-cd)pyrene, naphthalene, phenanthrene, perylene, and pyrene. Of these PAHs, benz(a)anthracene, benzo(a)pyrene, benzo(b)fluoranthene, benzo(k)fluoranthene, dibenzo(a,h)anthracene, indeno(1,2,3-cd)pyrene, and naphthalene are classified under California's Air Toxics Hot Spots Program as carcinogens (OEHHA 2015, 2020). While Li et al. (2003) did not evaluate PAH emissions specifically from cooking in residential kitchens, the study does show that PAHs are a group of toxic chemicals generated from cooking food and released to the air. These findings are consistent with information from the National Cancer Institute (2017) that PAHs are formed by the cooking of meats at high temperatures (regardless of fuel source). While the type of food or type of oil did not have significant differences, however, the type of food, oil used, and method of cooking all contributed to PM2.5 substantially more than the fuel source used.

Hu et al. (2012) derived $PM_{2.5}$ emission rates for the cooking of various food types, cooking methods, cooking oils, and cooking appliances based on data compiled from multiple, previously published studies. Hu et al. found little difference between gas ranges and electric ranges in emissions during cooking, but also found little difference between different types of food (e.g., meats vs. vegetables) and different types of cooking oils. Similarly, little difference was observed between grilling and frying, but oven cooking had much lower rates. The authors noted the minimal differences in emission rates was due to the high variability in results across multiple studies, resulting in large standard deviations on the mean emission rates.

The following three studies included gas fuels in addition to methane. O'Leary et al. (2019) conducted a laboratory study to determine $PM_{2.5}$ emission rates during the cooking of food. This study is of limited use as the type of gas used for the gas stove was not identified and only a limited number of meals were cooked. In addition, emission rates were reported as net emission rates that accounted for ventilation. Although actual $PM_{2.5}$ concentrations were not reported, results are consistent with other studies that report $PM_{2.5}$ emissions during the cooking of food.

Buonanno et al. (2009) evaluated UFP emissions produced during grilling and frying as a function of the food type, cooking temperature, and type of oil used for grilling and frying. Importantly, it was found that UFP emissions from gas stoves (butane and propane) were negligible as compared to UFP emissions during cooking. This study also found that the highest emissions for UFPs were generated from cooking fatty foods and increased heat resulted in increased UFP emissions for both gas and electric stoves.

See and Balasubramanian (2006) conducted similar studies in residential kitchens in Singapore. They did not report the type of gas used for the gas stove. Rather than focusing on emission rates, this study focused on PM particle number and size with a focus on UFPs. The authors concluded that deep frying emitted the highest number of particles and the highest portion of nanoparticles, followed by pan frying, stir frying, boiling, and steaming. In a subsequent study by the same two authors, See and Balasubramanian (2008) characterized the chemical nature of $PM_{2.5}$ released during cooking from different cooking methods, including steaming, boiling, stir frying, pan frying and deep frying. Air samples were collected during cooking and analyzed for $PM_{2.5}$, and collected $PM_{2.5}$ was analyzed for organic and inorganic ions, metals, and PAHs. Most metals and all PAHs were detected above baseline conditions, with deep frying producing the highest concentrations of metals and PAHs followed by pan frying, stir frying, boiling, and steaming.

Zhang et al. (2010) conducted a study at Texas A&M University at Kingsville, Texas using a 1,507 $ft^2$ single story residential home (R1), a 215 $ft^2$ student dorm (S1), and two 646 $ft^2$ apartments (A1 and A2). UFPs, $PM_{2.5}$, and black carbon (BC) were measured during various cooking activities including different fried foods (chicken & rice; fried egg & vegetables; boiled pasta & vegetables; onion & tomato; chicken, shrimp & vegetable; or chicken & rice at R1; and fried chicken only at S1, A1, and A2). An electric range was only used for the R1 experiments, always with the exhaust fan on and always at high heat. Thus, the only variables in the R1 experiments were the type of food and cooking time. For the S1, A1, and A2 fried chicken experiments, paired experiments were conducted using gas and electric ranges, exhaust fans on or off, and cooking temperatures set to either medium or high. However, as with the R1 experiments, the cooking time was variable in the S1, A1, and A2 experiments in order to achieve fully cooked meals. To account for the large number of variables, factor analysis was used to evaluate the effects of stove type, exhaust fan setting, and temperature on emissions. Factor analysis showed common trends of increased emissions for gas stoves as compared to electric stoves, at high temperatures as compared to medium temperatures, and with exhaust fans turned off as compared to on. We note that for the R1 scenario, which only used an electric range set to high temperature, the 24-hour average National AAQS of 35 $\mu g/m^3$ for $PM_{2.5}$ was exceeded in 4 of the 5 tests using different food types, with $PM_{2.5}$ concentrations reaching as high as 230.9 $\mu g/m^3$. For the S1, A1, and A2 tests, $PM_{2.5}$ concentrations while frying chicken with the exhaust fan on at medium temperature were 20.4 $\mu g/m^3$

and 18.8 µg/$m^3$ for electric stove (cooking time of 27 minutes) and gas stoves (cooking time of 23 minutes), respectively. In contrast, under the very same conditions, except with temperature set to high, $PM_{2.5}$ concentrations were 78.3 µg/$m^3$ and 98.1 µg/$m^3$ for electric stoves (cooking time of 11 minutes) and gas stoves (cooking time of 14 minutes), respectively.

Zhao et al. (2020) evaluated indoor air impacts associated with cooking on natural gas stoves at 23 low-income apartments equipped with Title 24 code-required ventilation equipment. The study was conducted with participation from current occupants with participation criteria that included routine daily use of a gas cooking appliance, prohibition from smoking, and to not use windows and doors for ventilation during the course of the one-week study. Indoor and outdoor air concentrations of formaldehyde, $PM_{2.5}$, $NO_2$, and carbon dioxide ($CO_2$) were measured over the course of the 1-week study. Only $PM_{2.5}$ and $NO_2$ results from the study are discussed here as formaldehyde is a well-known indoor air contaminant associated with building materials and outdoor air concentrations of $CO_2$ were not collected during the study even though outdoor air concentrations of formaldehyde, $PM_{2.5}$, and $NO_2$ were collected. Results showed that average $PM_{2.5}$ concentrations in apartment indoor and outdoor air were 7.7 µg/$m^3$ and 7.5 µg/$m^3$, respectively. Average $NO_2$ concentrations in apartment indoor and outdoor air were 18.8 µg/$m^3$ and 10.1 µg/$m^3$, respectively. Although there was little difference in indoor and outdoor $PM_{2.5}$ concentrations, indoor air $NO_2$ concentrations were higher than outdoor air concentrations. While these results suggest that increased concentrations of $NO_2$ may be due to the use of gas stoves during cooking, the average $NO_2$ concentration of 18.8 µg/$m^3$ is well below the 1-hour average AAQS of 100 ppb for $NO_2$. The 90$^{th}$ percentile indoor air $NO_2$ concentration in this study was 30 µg/$m^3$ and below the more stringent 1-hour average National AAQS of 100 ppb. In conclusion, this study showed that indoor air $PM_{2.5}$ concentrations were no different than outdoor air $PM_{2.5}$ concentrations, and that measured $NO_2$ concentrations were elevated but well below short-term average concentration standards and equal to or below the annual average California AAQS for $NO_2$ of 30 ppb.

Singer et al. (2017) conducted a study of pollutant emissions from gas stoves utilizing only nine homes in California that the authors rented from the occupants. All study home kitchens were equipped with gas ranges and in some cases ovens and broilers. The cooking scenarios during the experiments included stove top boiling of water and operating ovens and broilers with pans containing water. Food was not cooked. Two kitchens had neither range exhaust hoods nor forced air units (FAUs). One home had an FAU but no range exhaust hood. The remaining six homes had both range exhaust hoods and FAUs. Pollutants measured during the experiments included CO, $NO_2$, and $PM_{2.5}$. Under most cooking and ventilation scenarios, CO and $PM_{2.5}$ were below respective AAQSs. In the case of $NO_2$, the majority did not report $NO_2$ concentration levels exceeding the reference AAQS, but there were some 1-hour average concentration levels that minimally exceeded the AAQS (and one more significantly). However, the $NO_2$ concentration data were not tabulated in the publication (and were only reported in a bar graph) and therefore it was not possible for this review to quantitatively evaluate those exceedances relative to ventilation on/off conditions or other factors. However, based on the authors' conclusions presented below, it appears that proper range hood configuration and exhaust air flow would reduce $NO_2$ concentrations below the AAQS.

Singer et al. (2017) concluded that, "Based on the findings of this field study and the related, prior work referenced herein, the authors offer the following policy recommendations. Efforts should be made to increase awareness (a) that natural gas cooking burners are a source of air pollutant emissions into homes, and (b) that these pollutants can be controlled with an appropriately sized venting range hood or other kitchen exhaust ventilation. Building standards should require that range hoods have airflows of at least 95 L/s [201 cfm] and cover front burners or preferably demonstrate performance through a standard test [37]. Since the performance of most hoods is much better when cooking on the back cooktop burners, this practice should be encouraged to improve safety. Since cooking with electric burners also produces pollutants, kitchen exhaust ventilation should be available in all homes, and operated as a precaution whenever cooking occurs."

Finally, the principal author, Dr. Brett Singer, recently submitted comments to the CEC for the 2022 Energy Code Update Rulemaking on the topic of Air Pollutant Exposures from Natural Gas Cooking Burners (Singer 2020).[8] Dr. Singer echoed our caution on the use of chronic AAQSs to evaluate short-term cooking exposures, stating, "we note that caution should be exercised when considering how pollutant concentrations that result from an assumed cooking rate are compared to standards developed to protect against chronic exposure, as the annual ambient air quality standards are designed to do." Dr. Singer further states that, "Much of the commentary above has been focused on concentrations that can result when burners are used without venting. It is important to note that substantial data exists showing that use of venting range hoods can substantially reduce pollutant concentrations and occupant exposures."

In summary, review of these studies on indoor air impacts associated with food cooking reveals several common conclusions.

1. During the food cooking process, PM of varying particle sizes and numerous chemical compounds including metals, carcinogenic PAHs, acrylamide, heterocyclic amines, and other organic compounds are released from the food.
2. There is large variability in the nature of and amounts of PM and chemical compounds released during cooking of food. This variability appears to be due largely to the type of food, cooking temperature, and cooking methods, rather than the fuel type used. Increased temperature generally results in increased PM and chemical compound emissions.
3. Under some cooking scenarios using both gas and electric stoves, use of gas stoves resulted in higher food-related emissions from the same food during cooking, but this appears due to the cooking temperature and not to the gas itself. This difference may be due to the near instantaneous maximum temperature achieved with the gas stove flame as compared to electric stove coils.
4. The combustion by-products PM, CO, $CO_2$, and $NO_x$ are generated from natural gas stove burners during cooking. In contrast, electric stove coils during cooking emit PM, but not CO, $CO_2$, or $NO_x$. Both gas and electric stoves have negligible contributions to overall PM, which results more from the food being cooked.

**Issue 3: The type of appliance (natural gas or electric) used to cook food indoors is not a significant determinant of residential indoor air quality. While CO and $NO_x$ emissions and post-combustion formation of $NO_2$ are unique to gas ranges due to the combustion of natural gas, their concentrations in residential indoor air do not pose a health risk. Likewise, the trace elements in unburned natural gas have not been demonstrated to be at concentrations that would pose human health risk.**

Widespread efforts to address climate change associated with the use of fossil fuels such as coal, petroleum and natural gas have recently focused on natural gas stove use in residential and commercial kitchens. The focus of the climate change effort has been on the greenhouse gas emission potential, but there is increasing focus on health effects as a way to discourage gas appliance use in the home. The following discussion is focused on $NO_2$ and on recent claims relating to benzene, a VOC present in trace quantities in *unburned* natural gas.

[8] Included within Dr. Singer's comments were critical comments on the Zhu et al. (2020) UCLA study, on which we have previously commented. *See* Tormey, D. and S. Huntley, 2021. Issues that Render the Sierra Club/UCLA Study of *Effects of Residential Gas Appliances on Indoor and Outdoor Air Quality and Public Health in California* Not Useful for Decision-Making Purposes.

As discussed above under Issue 1, the literature indicates that the cooking of food results in net air emissions from the food that are more diverse and likely would pose a greater health risk than the CO, $NO_x$, and PM emissions from natural gas stoves or PM emissions from electric stoves. While $NO_2$ is not formed directly from the cooking of food per se, it is formed from the high temperature oxidation of atmospheric nitrogen ($N_2$) resulting in the formation of nitric oxide (NO), which is rapidly converted to $NO_2$.

$$N_2 + O_2 \rightarrow 2NO$$

$$2NO + O_2 \rightarrow 2NO_2$$

Of the compounds associated with the combustion of natural gas (PM, CO, $CO_2$, $NO_x$, and $NO_2$), there are AAQs for $PM_{2.5}$, $PM_{10}$, CO, and $NO_2$ (see Table 1). The AAQS may provide a point of reference where test data are similarly time-averaged, but in many cases, studies incorrectly compared peak measurements to time-averaged AAQS. [9]

Based on 60 identical cooking tests conducted in a controlled laboratory setting using natural gas stoves and various ventilation configurations, Dobbin et al. (2018) reported a maximum $NO_2$ concentration of 15 ppb, well below the reference 100 ppb 1-hour average NAAQS. Fortmann et al. (2001) measured background $NO_2$ concentrations with natural gas stove and oven operating for 10 minutes prior to the cooking of food, reporting average background $NO_2$ concentrations in the kitchen of 72.2 and 84.5 ppb for stove and oven, respectively, less than the reference 100 ppb 1-hour average NAAQS. In yet another cooking study using gas stoves, Zhao et al. (2020) reported a 1-hour average $NO_2$ concentration of 18.8 ppb, which is well below the reference 1-hour average NAAQS of 100 ppb. The 90$^{th}$ percentile 1-hour average indoor air $NO_2$ concentration in the study was 30 ppb, again below the 1-hour average NAAQS.

In summary, the data from studies on short-term $NO_2$ are inconsistent and represent a mix of peak concentrations and time-averaged concentrations that make comparison to 1-hour time averaged reference standards unhelpful and any conclusions regarding health effects difficult. The data do not consistently show exceedances of short-term reference standards. Moreover, in most cases, the data appear to show long-term $NO_2$ concentration levels below reference standards.

Two recent studies suggest that volatile organic compounds, or VOCs, are present in trace quantities in *unburned* natural gas and that leakage of natural gas from gas stoves when stoves were not in use releases these VOCs into indoor air. Because the natural gas is unburned, these studies are different from the other studies included in this review. The Lebel et al. (2022b) study was conducted using 159 gas stoves across seven geographic regions in California. Twelve VOCs were found to be entrained within the natural gas sampled: benzene, cyclohexane, ethylbenzene, 4-ethyltolune, heptane, hexane, m,p-xylene, o-xylene, toluene, and 1,2,4-trimethylbenzene. The detections and concentrations of these VOCs varied across geographic regions as well as across natural gas providers. The authors modeled indoor air concentrations based on their sampling results and prior reported leakage rates, but using very low air exchange rates and other unrealistic highly conservative assumptions. Specifically, half of the 140 scenarios modeled used a methane emission rate of 36 ml/hour and the other half used a "worst case" methane emission rate of 421 ml/hour (e.g., the equivalent of nearly 3 gallons of methane leaking into a home kitchen per day). As noted by the authors the benzene concentrations in some of the "worst case" scenarios (13 out of 70) resulting from such extreme leakage exceeded California's 8-hour reference exposure level (REL) of 0.94 ppb – but the natural gas would be smelled at those top concentration levels due to the odorant that is added for safety reasons. For the 70 modeling

[9] Note that the Dennekamp et al. (2001) study is excluded from discussion here since it was conducted in a sealed laboratory without ventilation and therefore does not correspond with realistic human exposure conditions.

scenarios that relied upon a methane emission rate of 36 ml/hour, none of the estimated indoor air benzene concentrations exceeded the REL of 0.94 ppb. Lebel et al. (2022a) reported that the age of the stoves used in their study of methane emission rates ranged up to 30 years and these “worst case” benzene modeling results illustrate the importance of proper appliance maintenance, especially as these stoves age.

The Michanowicz et al. (2022) study was conducted using 69 gas stoves at various locations throughout the greater Boston metropolitan area. While 296 non-methane VOCs were detected, besides methane and ethane, all VOCs were measured at extremely low mean levels of <0.0001%; the primary VOCs detected most frequently were benzene, toluene, ethyl benzene, xylenes, hexane, heptane, and cyclohexane. Similar to the Lebel et al. (2022b) study, Michanowicz et al. (2022) found variability in VOC concentrations across natural gas providers, but the study did not model indoor air quality impacts or exposure levels and was solely a hazard identification study. These studies do not directly relate to the issues addressed in this report (e.g., the effects of cooking on residential indoor air quality) because the gas stoves were not in use during the studies, but do highlight the importance of cooking appliance maintenance and ventilation. In addition, it is important to note that during actual gas stove use, these carbon-based VOCs present in natural gas would be expected to be fully combusted (e.g., oxidized to CO and $CO_2$) along with the primary natural gas constituent, methane. Moreover, while these studies highlighted benzene, benzene is a common constituent of urban air and has many common sources, including paint, adhesives, and tobacco smoke and is in common foods such as bananas, strawberries, potato chips, and avocados (USEPA 2007). The reported concentrations generally were at low levels; Michanowicz et al. (2022) estimated 0.004 ppb (based on the odorant threshold levels) while the USEPA (2007) reports the median outdoor air concentration at up to 34 ppb and indoor air concentration at up to 1.8 ppb.

**Issue 4: To date, there has not been a comprehensive human health risk assessment conducted to evaluate potential indoor air impacts to human health associated with the myriad chemicals released from food during the process of cooking. Nearly all studies published on the impacts of cooking on indoor air quality have focused on emissions and resulting concentrations of various chemical constituents, rather than any demonstrated health risk.**

There are many chemicals, including carcinogens, that are released during the cooking of food. The most critical question to ask regarding the impacts of cooking on indoor air quality is whether such impacts pose a human health risk, not whether ambient air quality standards that do not directly apply are exceeded. Review of the primary literature indicates that this has not yet been done. Following traditional human health risk assessment methods, health risks would be evaluated on a chemical-specific basis and on a cumulative effects basis whereby cumulative risks are the summation of individual chemical-specific risks, as applicable. In addition, and following traditional human health risk assessment methods, noncancer risks for most chemicals and cancer risks for carcinogenic chemicals would be evaluated separately (OEHHA 2015, USEPA 2014).

While the AAQS for CO, $PM_{2.5}$, $PM_{10}$, and $NO_2$ can be considered as reference points for noncancer toxicity metrics for those chemicals, where measured appropriately, they are not designed for this purpose, but instead reflect potential health effects of ambient air. In addition, AAQS do not exist for other toxic chemicals that have been shown to be released from food during the cooking process. For many of these “other” chemicals, both the USEPA and California’s Office of Environmental Health Hazard Assessment have applicable noncancer and cancer toxicity values that could be applied to existing indoor air concentration results to estimate potential health risks. Moreover, a comparative risk assessment would allow for the differentiation of health risks associated with natural gas combustion by-products with those associated with actually cooking food.

For the question posed at the start of this report: “which of these emission sources (air emissions from cooking food, electric burning, natural gas combustion) is the main driver of health risk?”, the lack of a human health risk assessment is the most significant data gap to our ability to answer the question. The weight of evidence, however, is that when it comes to the indoor air quality of cooking with electricity or natural gas, the health driver is what you are cooking, not the fuel you are using when cooking. And the most effective method to protect your health is to provide ventilation during cooking.

### Other Issues

In addition to the three major issues described above, we note three other issues in the table below in determining the drivers of human health risk from cooking food with gas or electric stoves.

| Issue | Facts Supporting the Issue | Relevance |
|---|---|---|
| Heating regimen for gas and electric stoves are vastly different. | Hanks et al. (2014) reported that electric stoves when turned up to high heat ramp up very slowly (7-8 minutes) to a maximum temperature of 743°C. The maximum flame temperature for methane burning in air is 1,949°C (Babrauskas 2006). In contrast to electric stoves, natural gas stoves are expected to reach maximum temperature almost instantaneously. | The relative differences in the airborne chemicals released during cooking on gas and electric stoves may be explained, in part, by differences in heating regimen including temperature gradient over the period of cooking. |
| Adequate ventilation is among the most important factors affecting indoor air quality. | Many of the indoor air studies reviewed were conducted in other U.S. states or in other countries where building codes may be vastly different than those in California. Specifically, under CEC (2022) Title 24 Building Efficiency Standards[10], a minimum exhaust airflow for enclosed kitchens of 300 CFM is required for vented kitchen range hoods, and 300 CFM or 5 ACH is required for other kitchen exhaust fans. | California has strict range hood and kitchen ventilation requirements. Studies from other U.S. states and from other countries likely over-state indoor air impacts associated with indoor food cooking and use of gas ranges. |
| The potential health hazards associated with the cooking of food indoors will not simply go away in the absence of systematic mitigation measures. | Multiple factors affect indoor air quality during the cooking of food indoors. These include ventilation, appliance maintenance, personal food choices, and the industrial and regulatory community's responsibility to educate the public on the hazards of cooking food indoors as well as methods for mitigating impacts on indoor air quality. | A significant take-away from this review is that cooking indoors is a fact of life. It is very traditional and complies with social historical norms. Nevertheless, the impacts from cooking food indoors can pose a health hazard if not mitigated through such measures as adequate ventilation, appliance maintenance, and education. |

[10] Title 24 Tables 150.0-E and 150.0-F

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