

# Lawrence Berkeley National Laboratory

## LBL Publications

### Title

Quantifying the Potential Health Impacts of Unvented Combustion in Homes — A Meta-Analysis

### Permalink

<https://escholarship.org/uc/item/2128n50v>

### Authors

Mesquita, P Jacob Bueno de  
Casquero-Modrego, Nuria  
Walker, Iain  
[et al.](#)

### Publication Date

2023-10-04

Peer reviewed



Building Technologies & Urban Systems Division  
Energy Technologies Area  
Lawrence Berkeley National Laboratory

# Quantifying the Potential Health Impacts of Unvented Combustion in Homes – A Meta-Analysis

P. Jacob Bueno de Mesquita  
Núria Casquero-Modrego  
Iain S. Walker  
Brennan D. Less  
Brett C. Singer

Energy Technologies Area  
October 2023

[Insert citation or DOI # here]



This work was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy,  
Building Technologies Office, of the U.S. Department of Energy  
under Contract No. DE-AC02-05CH11231.

## **Disclaimer**

This document was prepared as an account of work sponsored by the United States Government. While this document is believed to contain correct information, neither the United States Government nor any agency thereof, nor the Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or the Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof or the Regents of the University of California.

This work was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Building Technologies Office, of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

## **Also published as:**

Bueno de Mesquita, J.; Casquero-Modrego, N.; Walker, I.S.; Less, B.D.; Singer, B.C. (2023) "Quantifying the Potential Health Benefits of Home Electrification – A Meta-Analysis" 43rd AIVC-11th TightVent & 9th Venticool Conference, 4-5 October 2023, Copenhagen. [\[Insert citation or DOI # here\]](#)

## **ABSTRACT**

While a growing body of scientific literature describes the population health impacts of fossil fuel production and burning via climate and air pollution pathways, less is known about the health impacts of indoor combustion. This paper summarizes the results of studies from the last two decades that investigated the association between exposure to sources of unvented combustion pollutants in homes and a range of health outcomes. We found gas combustion to be associated with 6-28% (95% confidence intervals) increased odds of asthma symptoms, 4-51% increased odds of systemic symptoms, 7-81% increased odds of asthma medication use, and 3-12% increased risk of mortality. These findings can be used to improve public health, for example, by informing requirements for improved ventilation and source control, justifying switching to vented appliances, better regulation of device emissions and quantifying the benefits of electrification of end-uses. Dose-response relationships between human health, NO<sub>2</sub> exposure, and other by-products of combustion are not characterized with a high degree of precision. However, there is clear evidence of a wide range of health effects, even at low levels of exposure. Despite the various designs, geographic sites, length of follow-up, and study dates, we noted a level of consistency between the studies within the current meta-analysis, and with previous ones, which strengthens the level of confidence in our findings.

### **Keywords**

Health; gas combustion; gas cooking; gas heating; meta-analysis

## 1. Introduction

The primary consumers of fossil fuels in homes are: heating, hot water, cooking and clothes drying. Except for cooking and unvented heaters, these end-uses are required to have a vent to outside and only contaminate indoor air if their venting system fails. While venting combustion products contributes to outside air pollution that can then enter a home, in this paper we will focus on direct indoor sources only.

It is well established that the inhalation of fossil fuel combustion products leads to a range of adverse population health effects. Cooking and unvented heating are main indoor sources of NO<sub>2</sub>, ultrafine particles, and volatile organic compounds (VOCs) if not vented to outdoors (Lewis et al., 2023). A previous literature review (Less et al. 2022) discussing home energy performance provided a high-level summary of a few indoor air quality studies related to indoor combustion, but did not provide the in-depth health analysis that is the focus of this paper.

NO<sub>2</sub> is an irritant to the respiratory tract. Even short-term exposures can irritate the airways, drive inflammation, and lead to acute and chronic disease, especially among those with asthma (Barck et al., 2005; Vardoulakis et al., 2020; Lim et al., 2022). While particles are the most important contaminant of concern for health impacts, at least from Disability Adjusted Life Year (DALY) perspective (Logue et al., 2012; Morantes et al., 2022), most particle exposure is from non-residential sources such as transport, agriculture and industry. Therefore, in this review will focus on the next important contaminant of concern, i.e., NO<sub>2</sub>. A meta-analysis done by (Faustini et al., 2014) confirms that the effect of NO<sub>2</sub> was independent from PM, suggesting that NO<sub>2</sub> can drive health effects on its own. In addition, when the levels of NO<sub>2</sub> in a home are below the threshold limits, (< 15 ppb), it becomes challenging to observe any potential health effects.

Although the strong toxicological evidence for NO<sub>2</sub> is compelling enough to spur population health protective action, the toxicology is borne out in a number of epidemiological studies. Meta-analyses by (Khreis et al., 2017) and (Gruenewald et al., 2022) of epidemiological studies showed clear relationships with asthma development and have enabled modelling studies estimating the broader population impacts of reducing NO<sub>2</sub> exposures (e.g., (Knibbs et al., 2018; Achakulwisut et al., 2019; Jacobs et al., 2019; Hu et al., 2022)). (Lin et al., 2013) synthesized the available literature on gas stove use and found correlations with the two health outcomes they studied, asthma development and wheeze in children. This paper provides a 10-year update to Lin et al, to build on existing dose-response findings through the inclusion of studies published through April 2023 that reported on a broader set of potential adverse health effects like hospitalization, asthma symptoms and medication use.

## 2. Methodology

This study reviews research since the year 2000 on the health impacts associated with exposure to combustion-related contaminants in homes. We grounded the evaluation using literature related to interventions where gas combustion appliances were replaced, or effective engineering controls were implemented, including those where measured NO<sub>2</sub> was taken as the main exposure variable. We grounded the review in the landmark intervention studies conducted in Australia and New Zealand (Pilotto

et al., 2004; Howden-Chapman et al., 2008; Marks et al., 2010; Gillespie-Bennett et al., 2011), and a comprehensive meta-analysis focused on gas stove effects on cough and wheeze (Lin et al., 2013). We used Google Scholar to identify works citing these studies. We then applied inclusion and exclusion criteria to narrow the search to epidemiological studies that provide dose-response relationships between home combustion appliances and health outcomes.

We assessed study relevance and quality, leading to a final set of manuscripts. We included studies that used epidemiologic methods to investigate associations between health outcomes and the presence or use of unvented gas combustion appliances and/or measured NO<sub>2</sub> with results presented as effect estimates with confidence intervals. Studies were excluded that did not involve data collection post-2000, that did not focus on residential exposure, that had effect estimates that were already included by Lin and colleagues, and that did not include gas or oil-based cooking or heating sources. Wood burning was considered beyond the scope of this analysis, as were effect estimates of lung function. We considered meta-analyses that used pooled estimates from studies with lower risk of bias as evaluated by the WHO or other similar methodology.

In this study, the health outcomes primarily were associated with acute exposures. We categorized the health outcomes into 12 distinct categories.: 1) asthma symptoms including wheeze, cough, shortness of breath, chest tightness, respiratory symptoms, nasal symptoms, and difficulty breathing; 2) asthma symptom scores including ordinal scores 0-3 (3 as the most severe and 0 as no symptom) for wheeze, cough, overall asthma symptoms, upper respiratory, and lower respiratory symptoms; 3) systemic symptoms including poor/fair health, diarrhea, vomiting, ear infection stomach ache, eczema, sensitization, allergies, nighttime waking, and steroid use; 4) healthcare visits that were not hospitalizations or emergency room visits or changes to asthma management; 5) hospitalization or emergency room visits, 6) medication use including asthma preventer and reliever use; 7) nonpharmaceutical interventions including limiting activity; 8) neurological disease development including schizophrenia; 9) absences from school; 10) all-cause mortality; 11) cardiovascular mortality; 12) respiratory mortality.

We converted effect estimates with continuous, independent variables to effects per 20 ppb increase in NO<sub>2</sub>. We converted intervention studies to consider control groups as the numerator in effect estimate ratios. We used effect estimates that adjusted for confounders when available. We stratified pooled estimates by health outcome, categorical or continuous exposure, and effect estimate type (odds ratios (OR), risk ratios (RR), incident rate ratios (IRR)). We computed random effect pooled estimates where there were at least four effect estimates, accounting for variation in study populations, differences in study design, and a variety of health outcomes considered. For example, the outcome of “asthma symptoms” included effect estimates for cough, wheeze, respiratory symptoms, and others. Statistics and forest plots were generated by *R* v.4.2.1 with packages *meta* and *metafor*. The data and code for reproducibility can be found at <https://gitlab.com/jacobbueno/zapdos>.

### 3. Results

The search yielded 29 studies including 10 meta-analyses, 12 observational studies and 7 randomized controlled trials (RCTs) or quasi-experimental studies. In total, these included 184 effect estimates for a variety of health outcomes. Eleven of the studies focused exclusively on children with asthma, as part of randomized controlled trials or observational studies. An additional study included over 80% children with asthma. RCTs and observational studies often focused on unvented exposures from unvented gas heat and gas cooking. In contrast, the meta-analyses mostly focused on residential indoor NO<sub>2</sub> exposure from multi-year indoor air pollution monitoring. Intervention studies examined changes in exposure to combustion contaminants and associated health effects. Intervention activities included installing exhaust ventilation for combustion appliances or electric alternatives like heat pumps (Pilotto et al., 2004; Howden-Chapman et al., 2008; Free et al., 2010; Barnard et al., 2011; Gillespie-Bennett et al., 2011), a gas scrubber (Gent et al., 2022) or comparing homes with gas and appliances (Belanger et al., 2006; Willers et al., 2006; Boulic, 2012; Rice et al., 2020).

Average NO<sub>2</sub> level changes for unvented gas heat at home were reported in residences at 3.8 ppb (Howden-Chapman et al., 2008; Free et al., 2010), and in schools at 14.1 ppb (Marks et al., 2010), and 31.5 ppb (Pilotto et al., 2004). Belanger et al, showed an increase in average NO<sub>2</sub> of 17.3 ppb (Belanger et al., 2006), Comparing gas ranges with electric ranges in both multifamily and single-family homes. (Hansel et al., 2008) found that the presence of a gas stove, as well as the use of stove/oven and space heater for heat, is linked to higher indoor levels of NO<sub>2</sub>, which suggests modifiable sources of exposure. Those with gas stoves had 15.7 ppb (95% CI 6.9-24.6) times the NO<sub>2</sub> concentration and those with gas heaters had 4.4 ppb (95% CI -2.8-11.6) times the NO<sub>2</sub> concentration. In 24 high performance California homes, (B. Less et al., 2015) measured NO<sub>2</sub> in kitchens that used gas and electric cooking equipment and found average 6-day integrated NO<sub>2</sub> concentrations of 6.6 vs. 17.9 ppb in electric and gas cooking kitchens respectively. The California Healthy Homes Indoor Air Quality Study of 2011–2013 (Mullen et al., 2016), measured combustion contaminants for 6-day periods in 352 existing California dwellings (including the homes in Less et al.). They found that kitchen NO<sub>2</sub> concentrations were not significantly impacted by vented combustion appliances (6.5 vs. 7.6 ppb), while unvented gas cooking with and without other vented gas appliances led to significantly higher indoor concentrations (18 and 22 ppb, respectively). Similarly, Belanger et al 2006 found clear increases in NO<sub>2</sub> concentration in homes with gas versus electric cooking.

We considered NO<sub>2</sub> to be a main toxicant produced by indoor gas combustion (compared with electric appliances) or an indicator chemical of the combustion air pollution—including PM and VOCs—that could be related to health effects via inhalation exposure. Meta-analyses focused on indoor NO<sub>2</sub> concentrations found consistent relationships with all mortality with a 95% CIs of 3-12%, while a 10-year Danish birth cohort quantified risk of schizophrenia development at 2.18 (95% CI 1.69-2.85) times higher for each 20 ppb NO<sub>2</sub> increase (Horsdal et al., 2019). The range of health effects consistently associated with indoor, residential gas combustion over the last two decades shows that at population scale, substituting gas appliances for electric ones should reduce some adverse health effects, with associated health, economic, and social benefits. The studies highlight the elevated risk of symptoms and associated health problems for those with asthma, but also show that combustion appliance exposure could lead to asthma development and other cardiovascular, respiratory, and neurological diseases.



Samet and colleagues tracked daily symptoms in over 1,200 infants through 18 months of age and found that measured NO<sub>2</sub> concentrations at home, mostly below 20 ppb, were not associated with respiratory symptoms (Samet et al., 1993), suggesting there may be little risk for infants with low to modest NO<sub>2</sub> exposure, or among populations that are not already susceptible to respiratory health risks (e.g., those with asthma, or bronchopulmonary dysplasia). However, this study did not examine other health impacts such as respiratory infections, asthma exacerbation or initiation. Other studies included in our meta-analysis included infant populations along with older children, with mixed results (Belanger et al., 2006; Willers et al., 2006; Barnard et al., 2011; Rice et al., 2020). The 8-year prospective birth cohort by Willers et al reported a positive relationship between gas cooking and nasal symptoms, and a trend toward a positive relationship with asthma prevalence, but not eczema, wheeze, or sensitization (Willers et al., 2006). A cross-sectional study of children 12 years old or younger revealed strong, positive associations between gas stove use and wheeze, chest tightness, and shortness of breath, particularly among multi-family as opposed to single-family residences (Belanger et al., 2006). Barnard et al showed a slight risk of hospitalization associated with gas heating in a population inclusive of all ages, and Rice et al showed a nearly 600% increase in odds of hospitalization among children with bronchopulmonary dysplasia on respiratory support (Barnard et al., 2011; Rice et al., 2020). The detectable risk increases associated with indoor combustion sources appear to be modified by existing health vulnerability including asthma. The likelihood of increased risks with cumulative exposures raises concerns about health risks for communities already facing disproportionate burdens of toxic exposures, especially where there are already higher rates of asthma and other illnesses or vulnerability due to environmental exposures. Overall, the effect estimates trended toward a positive relationship between residential gas combustion, NO<sub>2</sub> exposure, and adverse health outcomes. There were no effect estimates with 95% CIs completely below the null, which would have been indicative of a statistically significant protective effect of the exposures on health risks.

*Asthma Symptoms and Symptom Scores.* The presence of gas versus electric appliances, mediated by whether the gas appliances were vented (e.g., flue for gas heater), was associated with 1.16 times the odds of reporting asthma symptoms (95% CI 1.06-1.28). There was little difference in the magnitude of effect between observational studies and RCTs, although there was greater precision among the observational studies. Table 1 summarizes odds ratios for a 20 ppb increase in average NO<sub>2</sub> exposure linked with combustion cooking and/or unvented heating. Each 20 ppb increase in NO<sub>2</sub> exposure linked with gas combustion was associated with 1.55 (95% CI 1.41-1.71) and 1.21 (95% CI 1.06-1.37) times higher odds of asthma symptoms, for RCTs and observational studies, respectively. The pooled OR of 1.33 (95% CI 1.19-1.49) may not be reliable given the lack of overlap in confidence intervals for RCTs and observational studies, yet the confidence interval ranges demonstrate a consistent, positive association with asthma symptom risk.

Fifteen effect estimates from two RCTs (Pilotto et al., 2004; Howden-Chapman et al., 2008) showed 1.38 (95% CI 1.19-1.61) times higher risk of asthma symptoms with gas appliance exposure. A prospective cohort with six months of follow up showed that measured NO<sub>2</sub> at home was associated with elevated incidence rates of a range of asthma symptoms including wheeze, cough, chest tightness, limited speech, and greater correlation of these symptoms with exercise. A pooled effects model of the six effect estimates in (Hansel et al., 2008), gave an 11% (95% CI 7-15) incident rate increase per 20 ppb increase in NO<sub>2</sub>. For each 20 ppb increase in measured indoor NO<sub>2</sub> level, another study reported 2.86 (95% CI



1.03-8.35) times higher odds of a unit increase in asthma symptom score (Belanger et al., 2013), and yet another (Gillespie-Bennett et al., 2011) reported 1.62 (95% CI 1.52-1.73) and 1.12 (95% CI 1.00-1.20) times higher odds of lower and upper respiratory symptoms, respectively. (Schachter et al., 2020) showed that the presence of a gas stove was associated with 2.82 (95% CI 1.10-7.24) times greater odds of an increased wintertime cough and wheeze score.

Two studies considered asthma incidence (Lin et al., 2013; Khreis et al., 2017). Pooled effect estimates and confidence intervals from Kreis and colleagues spanned above one and reached 2.08 (95% CI 1.45-2.94) for children less than 6 years of age. Lin et al., 2013 showed 32% (18-48%) and 12% (-12%-43%) increased odds of asthma incidence for presence of residential gas stove and 15 ppb NO<sub>2</sub> increase, respectively. Meta-analyses by Zheng and colleagues showed consistent but mild increases in emergency room visits or hospitalizations with increases in indoor NO<sub>2</sub> (Zheng et al., 2015, 2021). The 2015 study gave pooled risk ratios for asthma-related emergency room visits or hospitalizations of 1.07 (95% CI 1.05-1.09) for all ages. The 2021 study pooled risk ratios for the same outcome of 1.00 (95% CI 0.88-1.13) and 1.04 (95% CI 1.03-1.05) for increases in 1-hr maximum NO<sub>2</sub> and 24-hr average NO<sub>2</sub> concentrations.

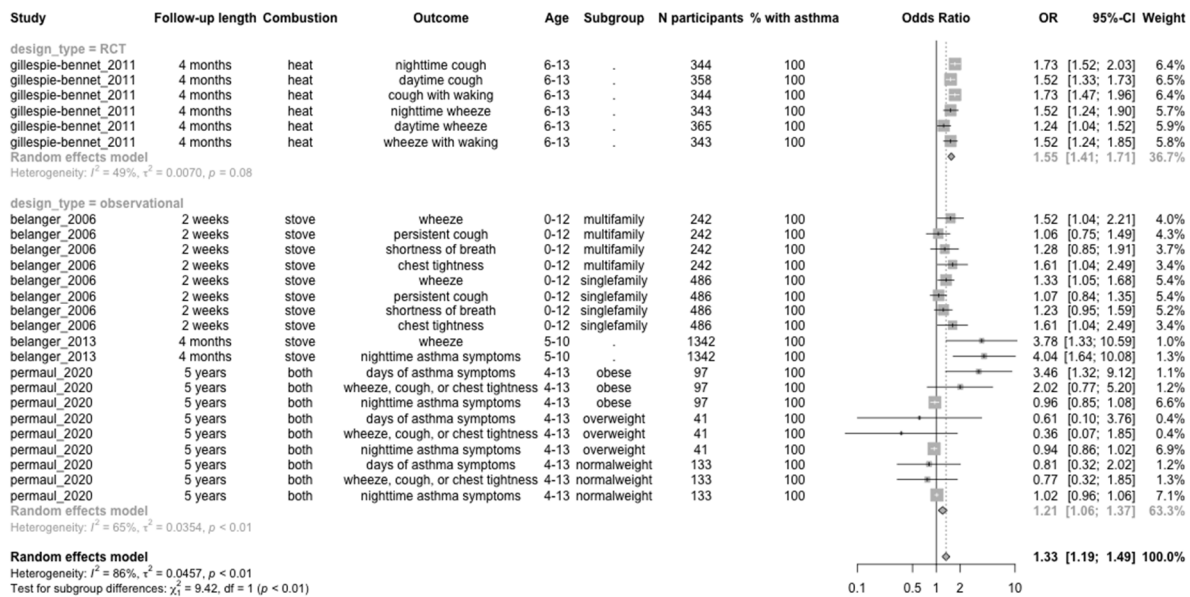
It should be noted that a few studies showed no or weak associations between gas combustion or NO<sub>2</sub> exposure and health outcomes under study in their respective investigations. The quasi-experimental study that was included used a retrospective matched cohort for nearly 1 million New Zealanders of all ages, mostly without asthma, for 3 years of follow up and found a very slight trend toward an increase in hospitalization rate for asthma, circulatory disease, respiratory disease, or RSV among homes without a heat pump, pellet burner, or flued gas heat intervention (IRR 1.04 95% CI 1.00-1.09) (Barnard et al., 2011). The same study failed to detect an effect for hospitalization for congestive heart failure or for mortality among those hospitalized for cardiovascular or respiratory disease. A prospective cohort study with 12 weeks of follow-up in Adelaide, Australia tracked NO<sub>2</sub> exposure at home and in school and showed mostly weak, non-statistically significant effects (Nitschke et al., 2006). They reported some mild effects for night-time breathing difficulty and night-time asthma attacks (RR 1.06 [1.02-1.10] and 1.08 [1.00-1.14]). An intervention trial with 5 weeks of particle filtration and NO<sub>2</sub> scrubbing showed only marginal reductions in measured NO<sub>2</sub> levels and no effect between NO<sub>2</sub> level and asthma symptom days during the final two weeks of treatment (Gent et al., 2022).

Gas stoves and unvented gas heaters can readily produce increases in NO<sub>2</sub> concentration associated with adverse health effects. Relationships between gas stove use and NO<sub>2</sub> levels reported by Hansel et al (2008), and Belanger et al (2006), are consistent with the work of others including (Simoni et al., 2004) who examined relationships between gas stove use time and pollutant levels. We note that exhaust ventilation can reduce but not eliminate gas stove emissions and relies upon consistent and proper operation, which is generally low (Sun & Singer, 2023). Many inner-city households are known to have gas stoves, often without exhaust ventilation (Breyse et al., 2005; Diette et al., 2007). The Baltimore home cohort conducted by Hansel et al, identified 14% of homes using gas stoves for heat, underscoring the intersection of environmental and energy injustice (Hansel et al., 2008). The higher magnitude of effects per unit increase in NO<sub>2</sub>, reported by Belanger et al (2006), for multi-family versus single-family housing suggests that the size of the health risk may be greater at higher exposure levels associated with greater gas stove use. Field studies in homes (e.g., (Francisco et al., 2010), and IAQ analyses

(Sherman et al., 2022)), have shown that NO<sub>2</sub> from unvented gas heaters regularly exceeds health guidelines, including spaces that meet minimum ventilation standards.

**Systemic symptoms.** We found evidence of a trend toward increased odds of systemic symptoms with gas combustion exposure, with a pooled OR of 1.25 (95% CI 1.04-1.51). The RCT effect estimates drove this trend in the pooled regression. Studies that reported effects as a function of continuous NO<sub>2</sub> exposure found similar results with OR of asthma medication use of 1.61 (95% CI 1.01-2.56) for each 20 ppb NO<sub>2</sub> increase.

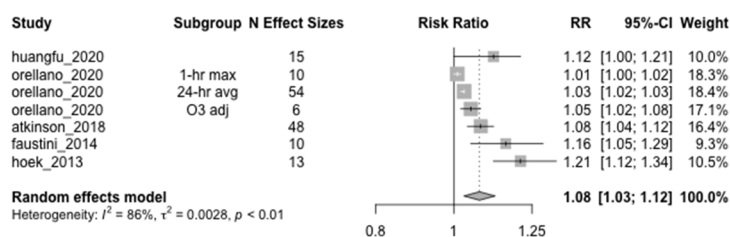
**Hospitalization, healthcare utilization and medication use.** A number of other observational studies and RCTs reported on risks associated with residential gas combustion. A cross sectional study with a 2-month prospective of survey data in Maryland showed a consistent, elevated trend toward higher risk of emergency room visit or hospitalization among children with bronchopulmonary dysplasia (Rice et al., 2020). Among those with respiratory support, the odds of hospitalization were 5.95 (95% CI 1.08-32.76) times greater for homes with gas combustion. Pooled analysis of studies evaluating the use of asthma medication showed 1.39 (95% CI 1.07-1.81) times higher odds with gas combustion exposure compared with electric appliance use or the addition of exhaust ventilation.



**Table 1.** Odds ratios for a 20 ppb increase in average NO<sub>2</sub> exposure linked with combustion cooking and/or heating.

A number of studies examined relationships between residential-level indoor NO<sub>2</sub> and population health risks. These are mostly summarized by meta-analyses, however we also included a Danish birth cohort following over 23,000 children for 10 years, which showed a 2.18 (95% CI 1.69-2.85) times higher risk for schizophrenia development for each 20 ppb increase in NO<sub>2</sub> (Horsdal et al., 2019). Meta-analyses mostly used a continuous NO<sub>2</sub> exposure variable to evaluate risk of mortality, asthma incidence, emergency room visits, and hospitalizations. The risk of mortality was consistently elevated, with 95% CIs ranging up to 39% above the null (Table 2). The ozone-adjusted model from (Orellano et al., 2020) gave similar results to the PM-adjusted model and both were not substantially different from pooled

estimates that did not adjust for co-pollutant measurements. Similarly, the effect of NO<sub>2</sub> was independent from PM in the meta-analysis done by (Faustini et al., 2014) according to their subset of studies that adjusted for multiple pollutants (n=7), suggesting that NO<sub>2</sub> can drive health effects on its own.



**Table 2.** Pooled meta-analysis all-cause mortality risk ratios for 20 ppb increases in indoor NO<sub>2</sub>.

## 4. Discussion

We reviewed the literature investigating associations between unvented residential gas combustion for cooking and unvented heating and potential health outcomes and found that observational studies, RCTs, and meta-analyses showed consistent increased risks for asthma symptoms, asthma development, school absence, hospitalization, and emergency room visits. Overall the health outcome with the most effect estimates for pooled analysis was the risk of asthma symptoms. The pooled estimates shows a 6-28% (95% CI) increase in risk of symptoms for unvented gas heating or presence of gas stoves compared with flued heating or electric heat or stoves. For each 20 ppb increase NO<sub>2</sub> concentration, the odds of asthma symptoms increased 19-49%. We observed elevated odds of asthma medication use across RCTs and observational studies with a pooled confidence interval of 7-81% higher odds with the presence of gas appliances.

Our results are consistent with a large body of scientific work in this area spanning decades. (Hasselblad et al., 1992) conducted a meta-analysis of the studies from the 1970's-1980's of indoor NO<sub>2</sub> exposure associated with gas stoves reported 20% increased odds of respiratory illness in children for each 16 ppb increase in NO<sub>2</sub> (Hasselblad et al., 1992). Lin et al considered studies through 2013 and found 6% (95% CI -1-3%) and 16% (95% CI 5-29%) increased odds of wheeze incidence with presence of residential gas stove and 15 ppb NO<sub>2</sub> increase, respectively. Our findings, using even more recent studies through 2023, were consistent with both of these previous meta-analyses.

Dose-response relationships between human health, NO<sub>2</sub> exposure, and other by-products of combustion are not well characterized. Furthermore, these relationships are mediated by numerous factors both inside and outside the built environment, including the presence and use of exhaust ventilation, the duration and types of food preparation, psychosocial stressors, and pre-existing health conditions. However, there is clear evidence of a wide range of health effects, even at low levels of exposure. A four-month prospective cohort by Belanger and colleagues showed a dose-response relationship between NO<sub>2</sub> exposure and wheeze, asthma symptoms, and asthma reliever medication use, with effects seen above a threshold of 6 ppb NO<sub>2</sub> (Belanger et al., 2013). Similarly, the year-long follow-up study by Boulic found that a 2-8 ppb increase was associated with a range of respiratory health outcomes. Perhaps it is not surprising then, that the underpowered trial by Gent and colleagues found

little relationship between health outcomes and the average 3-4 ppb NO<sub>2</sub> reductions, that were observed in dwellings already below health effects threshold limits.

The effect estimates, and confidence intervals presented here provide a window of reasonable risk levels for a variety of health outcomes and mortality, which can be used to extrapolate the health benefits of widespread measures to reduce the impacts of unvented combustion, including improved ventilation and source control, switching to vented appliances, better regulation of device emissions, and quantifying the benefits of electrification of end-uses. Despite the various designs, geographic sites, length of follow-up, and study dates, we noted a level of consistency between the studies within the current meta-analysis, and with previous ones, which strengthens the level of confidence in our findings. Studies were generally rigorously conducted, and variables were collected to allow for appropriate covariable adjustment. Given the small sample sizes, the pooled effect estimates are sensitive to the addition of new studies, given the small sample size. However, the reported confidence intervals are likely to be robust and provide perhaps a more helpful quantitative measure of risk given the inherent uncertainties and limitations of the epidemiologic studies required to detect population health effects in real-world conditions (Atkinson et al., 2018). New studies may be able to reduce sources of bias revealing even higher effect estimates and/or greater precision. Residential unvented combustion appliances pose a variety of serious health risks to people of all ages, but especially to children with asthma or other respiratory conditions.

## Acknowledgements

This work was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Building Technologies Office, of the U.S. Department of Energy under Contract No. DE-AC0205CH11231.

## References

- Achakulwisut, P., Brauer, M., Hystad, P., & Anenberg, S. C. (2019). Global, national, and urban burdens of paediatric asthma incidence attributable to ambient NO<sub>2</sub> pollution: Estimates from global datasets. *The Lancet Planetary Health*, 3(4), e166–e178. Scopus. [https://doi.org/10.1016/S2542-5196\(19\)30046-4](https://doi.org/10.1016/S2542-5196(19)30046-4)
- Atkinson, R. W., Butland, B. K., Anderson, H. R., & Maynard, R. L. (2018). Long-term Concentrations of Nitrogen Dioxide and Mortality: A Meta-analysis of Cohort Studies. *Epidemiology*, 29(4), 460. <https://doi.org/10.1097/EDE.0000000000000847>
- Barck, C., Lundahl, J., Halldén, G., & Bylin, G. (2005). Brief exposures to NO<sub>2</sub> augment the allergic inflammation in asthmatics. *Environmental Research*, 97(1), 58–66. <https://doi.org/10.1016/j.envres.2004.02.009>
- Barnard, L. T., Preval, N., & Howden-Chapman, P. (2011). *The impact of retrofitted insulation and new heaters on health services utilisation and costs, pharmaceutical costs and mortality.*
- Belanger, K., Gent, J. F., Triche, E. W., Bracken, M. B., & Leaderer, B. P. (2006). Association of Indoor Nitrogen Dioxide Exposure with Respiratory Symptoms in Children with Asthma. *American Journal of Respiratory and Critical Care Medicine*, 173(3), 297–303. <https://doi.org/10.1164/rccm.200408-1123OC>
- Belanger, K., Holford, T. R., Gent, J. F., Hill, M. E., Kezik, J. M., & Leaderer, B. P. (2013). Household Levels of Nitrogen Dioxide and Pediatric Asthma Severity. *Epidemiology*, 24(2), 320–330. <https://doi.org/10.1097/EDE.0b013e318280e2ac>
- Boulic, M. (2012). The association between mechanical ventilation, flue use in heaters and asthma symptoms. *Massey University*. <http://hdl.handle.net/10179/4082>

- Breyse, P. N., Buckley, T. J., Williams, D., Beck, C. M., Jo, S. J., Merriman, B., Kanchanaraksa, S., Swartz, L. J., Callahan, K. A., Butz, A. M., Rand, C. S., Diette, G. B., Krishnan, J. A., Moseley, A. M., Curtin-Brosnan, J., Durkin, N. B., & Eggleston, P. A. (2005). Indoor exposures to air pollutants and allergens in the homes of asthmatic children in inner-city Baltimore. *Environmental Research*, 98(2), Article 2. <https://doi.org/10.1016/j.envres.2004.07.018>
- Diette, G. B., Hansel, N. N., Buckley, T. J., Curtin-Brosnan, J., Eggleston, P. A., Matsui, E. C., McCormack, M. C., Williams, D. L., & Breyse, P. N. (2007). Home indoor pollutant exposures among inner-city children with and without asthma. *Environmental Health Perspectives*, 115, 1665–1669. <https://doi.org/10.1289/ehp.10088>
- Faustini, A., Rapp, R., & Forastiere, F. (2014). Nitrogen dioxide and mortality: Review and meta-analysis of long-term studies. *European Respiratory Journal*, 44(3), 744–753. <https://doi.org/10.1183/09031936.00114713>
- Francisco, P. W., Gordon, J. R., & Rose, B. (2010). Measured concentrations of combustion gases from the use of unvented gas fireplaces. *Indoor Air*, 20(5), 370–379. <https://doi.org/10.1111/j.1600-0668.2010.00659.x>
- Free, S., Howden-Chapman, P., Pierse, N., Viggers, H., & the Housing, H. and H. S. R. T. (2010). More effective home heating reduces school absences for children with asthma. *Journal of Epidemiology & Community Health*, 64(5), 379–386. <https://doi.org/10.1136/jech.2008.086520>
- Gent, J. F., Holford, T. R., Bracken, M. B., Plano, J. M., McKay, L. A., Sorrentino, K. M., Koutrakis, P., & Leaderer, B. P. (2022). Childhood asthma and household exposures to nitrogen dioxide and fine particles: A triple-crossover randomized intervention trial. *Journal of Asthma*, 0(0), 1–10. <https://doi.org/10.1080/02770903.2022.2093219>
- Gillespie-Bennett, J., Pierse, N., Wickens, K., Crane, J., Howden-Chapman, P., & Team, and the H. H. and H. S. R. (2011). The respiratory health effects of nitrogen dioxide in children with asthma. *European Respiratory Journal*, 38(2), 303–309. <https://doi.org/10.1183/09031936.00115409>
- Gruenewald, T., Seals, B. A., Knibbs, L. D., & Hosgood, H. D. (2022). Population Attributable Fraction of Gas Stoves and Childhood Asthma in the United States. *International Journal of Environmental Research and Public Health*, 20(1), 75. <https://doi.org/10.3390/ijerph20010075>
- Hansel, N. N., Breyse, P. N., McCormack, M. C., Matsui, E. C., Curtin-Brosnan, J., Williams, D. L., Moore, J. L., Cuhnan, J. L., & Diette, G. B. (2008). A longitudinal study of indoor nitrogen dioxide levels and respiratory symptoms in inner-city children with asthma. *Environmental Health Perspectives*, 116(10), Article 10. <https://doi.org/10.1289/Ehp.11349>
- Hasselblad, V., Eddy, D. M., & Kotchmar, D. J. (1992). Synthesis of Environmental Evidence: Nitrogen Dioxide Epidemiology Studies. *Journal of the Air & Waste Management Association*, 42(5), 662–671. <https://doi.org/10.1080/10473289.1992.10467018>
- Horsdal, H. T., Agerbo, E., McGrath, J. J., Vilhjálmsón, B. J., Antonsen, S., Closter, A. M., Timmermann, A., Grove, J., Mok, P. L. H., Webb, R. T., Sabel, C. E., Hertel, O., Sigsgaard, T., Erikstrup, C., Hougaard, D. M., Werge, T., Nordentoft, M., Børghlum, A. D., Mors, O., ... Pedersen, C. B. (2019). Association of Childhood Exposure to Nitrogen Dioxide and Polygenic Risk Score for Schizophrenia With the Risk of Developing Schizophrenia. *JAMA Network Open*, 2(11), Article 11. <https://doi.org/10.1001/jamanetworkopen.2019.14401>
- Howden-Chapman, P., Pierse, N., Nicholls, S., Gillespie-Bennett, J., Viggers, H., Cunningham, M., Phipps, R., Boulic, M., Fjällström, P., Free, S., Chapman, R., Lloyd, B., Wickens, K., Shields, D., Baker, M., Cunningham, C., Woodward, A., Bullen, C., & Crane, J. (2008). Effects of improved home heating on asthma in community dwelling children: Randomised controlled trial. *BMJ*, 337, a1411. <https://doi.org/10.1136/bmj.a1411>
- Hu, Y., Ji, J. S., & Zhao, B. (2022). Restrictions on indoor and outdoor NO<sub>2</sub> emissions to reduce disease burden for pediatric asthma in China: A modeling study. *The Lancet Regional Health - Western Pacific*, 24, 100463. <https://doi.org/10.1016/j.lanwpc.2022.100463>
- Jacobs, P., Borsboom, W., & Gids, W. de. (2019). *Indoor air quality in Nearly Zero Energy Buildings, reduction of exposure*. <https://www.aivc.org/resource/indoor-air-quality-nearly-zero-energy-buildings-reduction-exposure>
- Khreis, H., Kelly, C., Tate, J., Parslow, R., Lucas, K., & Nieuwenhuijsen, M. (2017). Exposure to traffic-related air pollution and risk of development of childhood asthma: A systematic review and meta-analysis. *Environment International*, 100, 1–31. <https://doi.org/10.1016/j.envint.2016.11.012>
- Knibbs, L. D., Woldeyohannes, S., Marks, G. B., & Cowie, C. T. (2018). Damp housing, gas stoves, and the burden of childhood asthma in Australia. *Medical Journal of Australia*, 208(7), 299–302. <https://doi.org/10.5694/mja17.00469>
- Less, B. D., Casquero-Modrego, N., & Walker, I. S. (2022). Home Energy Upgrades as a Pathway to Home Decarbonization in the US: A Literature Review. *Energies*, 15(15), 5590. <https://doi.org/10.3390/en15155590>
- Less, B., Mullen, N., Singer, B., & Walker, I. (2015). Indoor air quality in 24 California residences designed as high-performance homes. *Science and Technology for the Built Environment*, 21(1), 14–24. <https://doi.org/10.1080/10789669.2014.961850>

- Lewis, A. C., Jenkins, D., & Whitty, C. J. M. (2023). Indoor air pollution: Five ways to fight the hidden harms. *Nature Comment*, 614.
- Lim, Y.-H., Hersoug, L.-G., Lund, R., Bruunsgaard, H., Ketzel, M., Brandt, J., Jørgensen, J. T., Westendorp, R., Andersen, Z. J., & Loft, S. (2022). Inflammatory markers and lung function in relation to indoor and ambient air pollution. *International Journal of Hygiene and Environmental Health*, 241, 113944. <https://doi.org/10.1016/j.ijheh.2022.113944>
- Lin, W., Brunekreef, B., & Gehring, U. (2013). Meta-analysis of the effects of indoor nitrogen dioxide and gas cooking on asthma and wheeze in children. *International Journal of Epidemiology*, 42(6), 1724–1737. <https://doi.org/10.1093/ije/dyt150>
- Logue, J. M., Price, P. N., Sherman, M. H., & Singer, B. C. (2012). A Method to Estimate the Chronic Health Impact of Air Pollutants in U.S. Residences. *Environmental Health Perspectives*, 120(2), 216–222. <https://doi.org/10.1289/ehp.1104035>
- Marks, G. B., Ezz, W., Aust, N., Toelle, B. G., Xuan, W., Belousova, E., Cosgrove, C., Jalaludin, B., & Smith, W. T. (2010). Respiratory Health Effects of Exposure to Low-NOx Unflued Gas Heaters in the Classroom: A Double-Blind, Cluster-Randomized, Crossover Study. *Environmental Health Perspectives*, 118(10), 1476–1482. <https://doi.org/10.1289/ehp.1002186>
- Morantes, G., Jones, B., Sherman, M., & Molina, C. (2022). *Health impacts of indoor air contaminants determined using the DALY metric*. 774–783.
- Mullen, N. A., Li, J., Russell, M. L., Spears, M., Less, B. D., & Singer, B. C. (2016). Results of the California Healthy Homes Indoor Air Quality Study of 2011–2013: Impact of natural gas appliances on air pollutant concentrations. *Indoor Air*, 26(2), 231–245. <https://doi.org/10.1111/ina.12190>
- Nitschke, M., Pilotto, L. S., Attewell, R. G., Smith, B. J., Pisaniello, D., Martin, J., Ruffin, R. E., & Hiller, J. E. (2006). A Cohort Study of Indoor Nitrogen Dioxide and House Dust Mite Exposure in Asthmatic Children. *Journal of Occupational and Environmental Medicine*, 48(5), 462–469.
- Orellano, P., Reynoso, J., Quaranta, N., Bardach, A., & Ciapponi, A. (2020). Short-term exposure to particulate matter (PM10 and PM2.5), nitrogen dioxide (NO2), and ozone (O3) and all-cause and cause-specific mortality: Systematic review and meta-analysis. *Environment International*, 142, 105876. <https://doi.org/10.1016/j.envint.2020.105876>
- Permaul, P., Gaffin, J. M., Petty, C. R., Baxi, S. N., Lai, P. S., Sheehan, W. J., Camargo, C. A., Gold, D. R., & Phipatanakul, W. (2020). Obesity may enhance the adverse effects of NO2 exposure in urban schools on asthma symptoms in children. *Journal of Allergy and Clinical Immunology*, 146(4), 813-820.e2. <https://doi.org/10.1016/j.jaci.2020.03.003>
- Pilotto, L. S., Nitschke, M., Smith, B. J., Pisaniello, D., Ruffin, R. E., McElroy, H. J., Martin, J., & Hiller, J. E. (2004). Randomized controlled trial of unflued gas heater replacement on respiratory health of asthmatic schoolchildren. *International Journal of Epidemiology*, 33(1), 208–214. <https://doi.org/10.1093/ije/dyh018>
- Rice, J. L., McGrath-Morrow, S. A., & Collaco, J. M. (2020). Indoor Air Pollution Sources and Respiratory Symptoms in Bronchopulmonary Dysplasia. *The Journal of Pediatrics*, 222, 85-90.e2. <https://doi.org/10.1016/j.jpeds.2020.03.010>
- Samet, J. M., Lambert, W. E., Skipper, B. J., Cushing, A. H., Hunt, W. C., Young, S. A., McLaren, L. C., Schwab, M., & Spengler, J. D. (1993). Nitrogen dioxide and respiratory illnesses in infants. *The American Review of Respiratory Disease*, 148(5), 1258–1265. <https://doi.org/10.1164/ajrccm/148.5.1258>
- Schachter, E. N., Rohr, A., Habre, R., Koutrakis, P., Moshier, E., Nath, A., Coull, B., Grunin, A., & Kattan, M. (2020). Indoor air pollution and respiratory health effects in inner city children with moderate to severe asthma. *Air Quality, Atmosphere & Health*, 13(2), 247–257. <https://doi.org/10.1007/s11869-019-00789-3>
- Sherman, M., Fairey, P., & Crawford, R. (2022). Impacts of Unvented Space Heaters. *ASHRAE Journal*, 64(5), 32-34,36,38-42,44,46-49.
- Simoni, M., Scognamiglio, A., Carrozzi, L., Baldacci, S., Angino, A., Pistelli, F., Pede, F. D., & Viegi, G. (2004). Indoor exposures and acute respiratory effects in two general population samples from a rural and an urban area in Italy. *Journal of Exposure Science & Environmental Epidemiology*, 14(1), Article 1. <https://doi.org/10.1038/sj.jea.7500368>
- Sun, L., & Singer, B. C. (2023). Cooking methods and kitchen ventilation availability, usage, perceived performance and potential in Canadian homes. *Journal of Exposure Science & Environmental Epidemiology*. <https://doi.org/10.1038/s41370-023-00543-z>
- Vardoulakis, S., Giagloglou, E., Steinle, S., Davis, A., Smeuwenhoek, A., Galea, K. S., Dixon, K., & Crawford, J. O. (2020). Indoor Exposure to Selected Air Pollutants in the Home Environment: A Systematic Review. *International Journal of Environmental Research and Public Health*, 17(23), Article 23. <https://doi.org/10.3390/ijerph17238972>
- Willers, S. M., Brunekreef, B., Oldenwening, M., Smit, H. A., Kerkhof, M., De Vries, H., Gerritsen, J., & De Jongste, J. C. (2006). Gas cooking, kitchen ventilation, and asthma, allergic symptoms and sensitization in young children – the PIAMA study. *Allergy*, 61(5), 563–568. <https://doi.org/10.1111/j.1398-9995.2006.01037.x>

- Zheng, X., Ding, H., Jiang, L., Chen, S., Zheng, J., Qiu, M., Zhou, Y., Chen, Q., & Guan, W. (2015). Association between Air Pollutants and Asthma Emergency Room Visits and Hospital Admissions in Time Series Studies: A Systematic Review and Meta-Analysis. *PLOS ONE*, *10*(9), e0138146. <https://doi.org/10.1371/journal.pone.0138146>
- Zheng, X., Orellano, P., Lin, H., Jiang, M., & Guan, W. (2021). Short-term exposure to ozone, nitrogen dioxide, and sulphur dioxide and emergency department visits and hospital admissions due to asthma: A systematic review and meta-analysis. *Environment International*, *150*, 106435. <https://doi.org/10.1016/j.envint.2021.106435>