Literature Review on the Impacts of Residential Combustion

Addendum to the 2022 Report

April 2025

American Lung Association

ICF

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April 2025

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Water heater: Charlote May. https://www.pexels.com/photo/interior-of-kitchen-with-brick-wall-decorated-with-wicker-baskets-5824493/

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Acronyms and Abbreviations

Term	Definition
ACT	Asthma Control Test
AHS	American Housing Survey
BC	black carbon
BP	blood pressure
BTEX	benzene, toluene, ethylbenzene, and xylenes
CAP	criteria air pollutant
CH_4	methane
CI	confidence interval
CO	carbon monoxide
CO_2	carbon dioxide
CO_2e	carbon dioxide equivalent
COPD	chronic obstructive pulmonary disease
DBP	diastolic blood pressure
EIA	Energy Information Administration
EPA	U.S. Environmental Protection Agency
FeNO	fractional exhaled nitric oxide
FEV1	forced expiratory volume in one second
FVC	forced vital capacity
GHG	greenhouse gas(es)
HAP	hazardous air pollutants (also known as toxic air contaminants (TAC) or air toxics)
HONO	nitrous acid (also represented as HNO_2)
HVAC	heating, ventilation, and air conditioning
IAQ	indoor air quality
IRC	indoor residential combustion
LMIC	low- and middle-income country(ies)
LPG	liquified petroleum gas
LRI	lower respiratory infection
MERV	minimum efficiency reporting value
MeSH	medical subject headings
NEI	National Emissions Inventory
NH_3	ammonia
NLM	National Library of Medicine
NO_2	nitrogen dioxide
NO_x	nitrogen oxides (including nitric oxide and nitrogen dioxide)
N_2O	nitrous oxide
OAQ	outdoor air quality
OR	odds ratio
PAC	portable air cleaner
PAH	polycyclic aromatic hydrocarbon

Term	Definition
PM	particulate matter, which may be reported by size as PM_X, where X is the particle diameter in micrometers. Common size categories include PM_{10} (PM with diameter less than 10 µm), $PM_{2.5}$ (2.5 µm), PM_1 (1 µm), $PM_{0.1}$ (0.1 µm, commonly referred to as ultrafine particulate (UFP))
POM	particulate organic matter
ppb	parts per billion
ppbv	parts per billion volume
RECS	Residential Energy Consumption Survey
RMSSD	root mean square of successive differences
RWC	residential wood combustion
SBP	systolic blood pressure
SO_2	sulfur dioxide
TB	tuberculosis
TIAB	titles and abstracts
UFP	ultrafine particulate
VOC	volatile organic compound
WHO	World Health Organization

1 Introduction

In 2022, ICF collaborated with the American Lung Association to conduct a literature review on the various sources and impacts of indoor residential combustion (IRC) in the United States, including its impacts on human health and outdoor air quality. That review resulted in a report titled "Literature Review on the Impacts of Residential Combustion" (hereafter "2022 report"), which summarized findings from literature published between 2000 and January/February 2022, focusing on four research areas:

(1) Sources of IRC and their prevalence in U.S. homes,

(2) Emission profiles from IRC appliances and their impacts on indoor air quality (IAQ),

(3) The contributions of IRC appliances to outdoor air quality and climate change, and

(4) The health impacts from indoor and outdoor exposure to emissions from IRC appliances.

As examined in the 2022 report, in addition to electricity, IRC is used in approximately two-thirds of U.S. households for space or water heating, clothes drying, cooking, decoration (fireplaces), and other uses. More than half of those households use natural gas, primarily for space and water heating and for cooking. About 1 in 7 U.S. households use other fossil fuels (e.g., propane, fuel oil, or kerosene), while about 1 in 10 use wood as a secondary source of space heating. IAQ is impacted by air pollutant emissions from combustion appliances, including carbon monoxide (CO), nitrogen oxides (NOx), particulate matter (PM) and polycyclic aromatic hydrocarbons (PAHs) from gas appliances, and CO, NOx, PM, PAHs, benzene, and chromium from residential wood combustion (RWC). Exposure to these air pollutants has been shown to have detrimental health effects, and indoor exposure is of particular concern given the large proportion of time people in the United States spend indoors. Additionally, since indoor combustion appliances are vented to the outdoors, they contribute to ambient air pollution and climate change, and related health impacts.

Since 2022, research has continued to expand our understanding of the impacts of combustion occurring within the home on air quality, climate change, and human health. This Addendum updates the 2022 literature review and report to cover literature published during January 2021–January 2025, with an emphasis on literature covering impacts on outdoor air quality and climate change (research area #3) and health impacts (research area #4). We assessed peer-reviewed, scientific literature, written in English, with a specific link to IRC in the United States.

As in the 2022 report, we focus on the impacts of combustion appliances designed for use within the building envelope—those used for cooking, space and water heating, clothes drying, etc. Some sources of IRC are not within the scope of this report, including incense burning, candle burning, tobacco smoke, hobbies (involving welding, woodburning, and soldering), and occasional use of outdoor equipment within the building envelope (such as idling of cars or lawn equipment in enclosed garages). We also do not evaluate the impacts of residential combustion that typically occurs outside the home, such as barbecuing and pool heating.

The research areas of interest continue to belong in active broad research domains, such as air quality and climate implications of human activity, environmental health, etc. Accordingly, our bibliographic database searches produced thousands of results. Specifically, we retrieved 8,168 unique articles from bibliographic database searches (PubMed, EBSCO, Google Scholar). Overlaps occur across these results sets, with some articles found by multiple searches. This count does not include several articles added post-hoc. However, this value indicates the volume of the material identified.

Exhaustive review of all retrieved articles was not the scope of the original project or this update.[1] Given the resources available for this project, we aimed to review a fraction of the identified content, targeting articles that addressed the impacts of IRC in the United States. As done in the 2022 review, to bring this volume of material into scope, we relied on pre-screening prioritization tools and large language model (LLM) prompts to identify 160 studies for manual screening (see methodological details in Appendix A). These 160 articles formed the primary review set for this report, with another 4,941 articles identified as potentially relevant for a future systematic review effort. Studies containing only foreign country or city terms in their titles or abstracts (n=3,067) were deemed not relevant and excluded from screening. During manual screening, we identified 40 studies for full-text review, prioritizing studies covering the topics of interest with clear IRC components and U.S. relevance.

In this report, we identify and synthesize the information collected (Section 2). We also discuss the findings and limitations of this review (Section 3) and identify opportunities for future research activities that could build on the work summarized in the 2022 report and this addendum (Section 4). This report is accompanied by two appendices. Appendix A provides details of the research methodology. Appendix B provides a full listing of the articles cited in the report, as well as the 4,941 articles with pre-screening prioritization that were not selected for manual review or prioritized for inclusion in this report. This appendix complements Section 4 by providing references for the full set of articles identified as potentially relevant through our literature search update.

[1] As scoped, this project update assumed that a maximum of 160 references resulting from the peer-reviewed literature search would undergo initial title-abstract screening, and no more than 40 studies would require full-text review and undergo synthesis.

2 Findings

Below, we present our findings on updates for the two research areas: ambient air pollution and climate impacts (i.e., research area #3; Section 2.1) and health impacts of IRC (i.e., research area #4; Section 2.2). In each section, we (1) include the gaps previously identified, (2) indicate whether the newly reviewed literature supplements those gaps, and (3) provide a summary of the findings from studies reviewed for this addendum.

2.1. Ambient Air Pollution and Climate Change Impacts

As discussed in the 2022 report, although many IRC appliances are automatically vented to the outdoors, users control venting of natural gas cooking appliances through exhaust fans. Due to air exchange, even unvented pollutants emitted indoors are eventually released outdoors. Thus, IRC can contribute significantly to outdoor air pollution, including elevated concentrations of hazardous air pollutants (HAPs), criteria air pollutants (CAPs), and greenhouse gases (GHGs). Woodsmoke is of particular concern due to its potential to contribute to degradation of regional outdoor air quality. Although wood fuels may be considered carbon neutral, woodsmoke has a climate effect through its substantial black carbon (BC) component. Nationally, it is the dominant source of HAPs emitted to the outdoors from residential combustion. Outdoor woodsmoke from local consumption and transported pollution is observed in rural and urban areas, although the relative contribution of woodsmoke tends to be largest in smaller towns. Natural gas has much lower PM and BC emissions than wood when combusted, but it contributes to global warming via emissions of carbon dioxide (CO_2) when combusted and releases of methane (CH_4) both at the appliance and from leaks within and upstream of the residence. CH_4 is 56 times more potent than CO_2 in global warming potential over a 20-year period (United Nations Climate Change, 2022).

Table 1 is an updated version of Table 8 in the 2022 report, using the most current data from the U.S. Environmental Protection Agency (EPA) National Emissions Inventory (NEI; United States Environmental Protection Agency, 2020), whereas the original Table 8 used the 2017 NEI. The values are emissions to the outdoors only, and some of the data may include combustion with outdoor appliances like grills. The data include 2020 data from the Energy Information Administration (EIA) and state agencies, the latest available census housing information, and emission factors from various EPA sources. For RWC in particular, the 2020 data include improved methodologies, updated data from the EIA, and new emission factors from wood stoves. For these reasons, emissions from the 2017 and 2020 NEIs are not easily comparable for the purpose of observing time trends. For example, the emissions to the outdoors of $PM_{2.5}$ from RWC were about 45% higher in the 2020 inventory relative to the 2017 inventory. Most of the increase was due to residential activity changes (~35%), while the other 10% was due to updated emission factors. Therefore, we present these 2020 values as-is, representing the most recent data available from the NEI, without comparison to the 2017 values.

As seen in Table 1, in 2020 natural gas was responsible for about two-thirds of national residential combustion emissions to the outdoors of ammonia (NH_3) and NOx. RWC in 2020 was responsible for over 85% of all residential combustion emissions to the outdoors of sulfur dioxide (SO_2) and over 95% for CO, volatile organic compounds (VOC), PM, and a range of toxic compounds including PAHs. Residential combustion using oil (distillate oil and kerosene) and other fuels (bituminous coal and liquified petroleum gas (LPG)) in 2020 were primarily associated with emissions to the outdoors of NOx, for which these fuels altogether comprised 20% of the inventory of residential combustion emissions to the outdoors of NOx.

Table 1. 2020 National Total Emissions to the Outdoors of Criteria Air Pollutants (in tons) and Total Hazardous Air Pollutants (in pounds) from Residential Combustion and Overall National Total [a]

Residential Combustion Fuel Source	Ammonia	Carbon Monoxide	Nitrogen Oxides	PM_{10} Primary [b]	$PM_{2.5}$ Primary [b]	Sulfur Dioxide	Volatile Organic Compounds	Total HAP (pounds)
Natural Gas	44,705	93,643	215,690	2,689	2,509	1,260	12,591	360,462
Oil [c]	1,415	8,236	28,379	3,465	3,118	571	1,007	137,654
Wood	22,862	3,159,455	49,794	488,914	485,077	12,587	459,848	351,117,429
Other [d]	6	10,371	36,694	47	43	26	1,149	42,374
Total, Residential Combustion	68,988	3,271,705	330,557	495,115	490,747	14,444	474,595	351,657,919
Total, All Categories [e]	5,482,484	66,152,007	8,914,539	16,781,432	5,821,037	1,841,380	46,187,246	11,933,554,939

Data source: United States Environmental Protection Agency (2020)

[a] Some of these data on residential combustion may include combustion with outdoor appliances like grills.

[b] PM_{10} and $PM_{2.5}$ values are reported as data for both filterable ("filt") and condensable ("cond") PM.

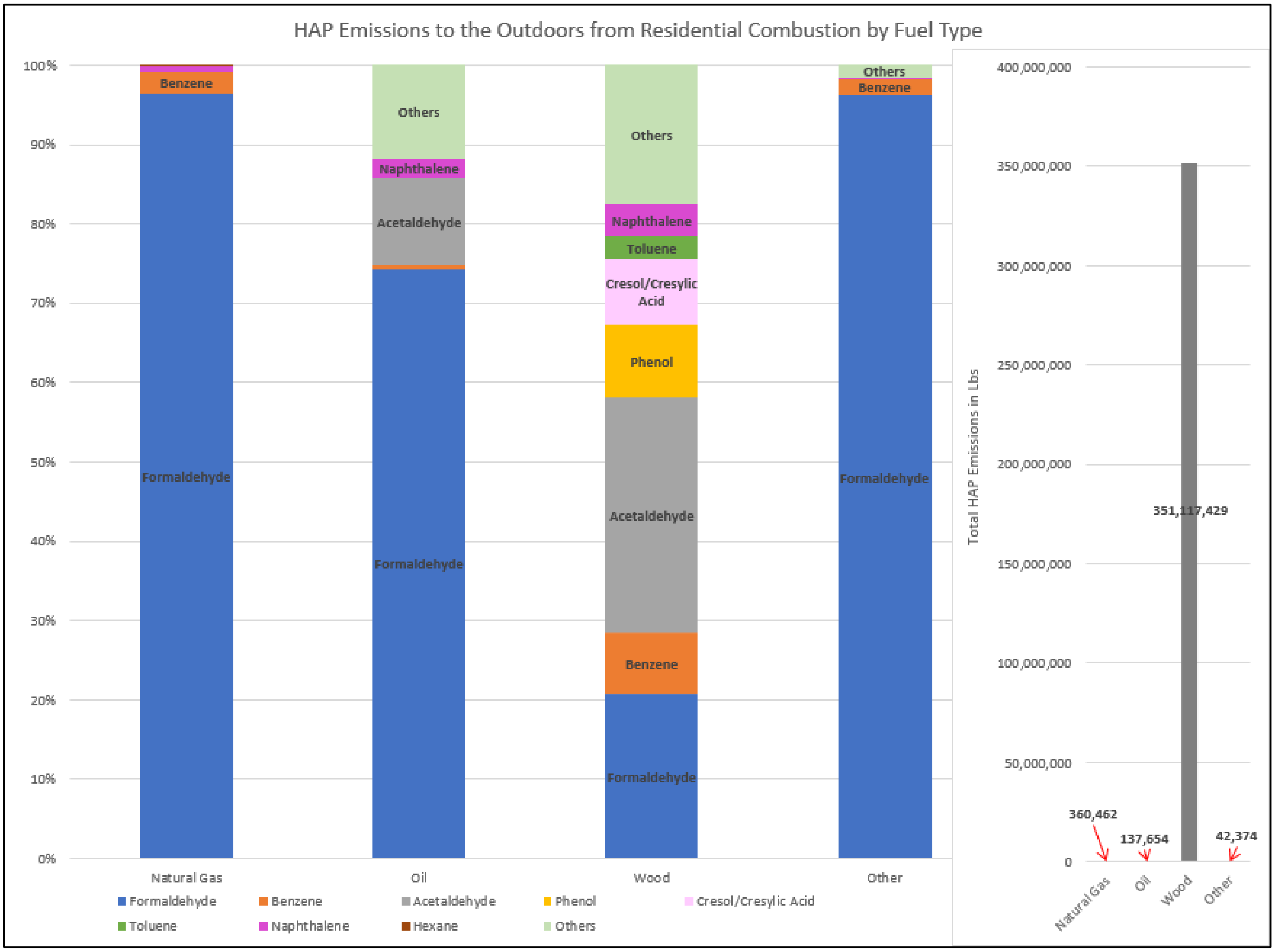
[c] Oil includes distillate oil and kerosene.

[d] "Other" includes bituminous coal and liquified petroleum gas.

[e] Value is the total national inventory of all categories reported (residential combustion as well as other categories like industrial, wildfires, vehicles, etc.).

Figure 1 shows the relative national-level contribution of each reported HAP to demonstrate the relative importance by fuel type for outdoor emissions from residential combustion. Figure 1 is an updated version of Figure 8 from the 2022 report. It uses the same data source as Table 1, and the discussion above regarding Table 1 also applies to Figure 1. For natural gas, formaldehyde was the main HAP emitted to the outdoors from residential combustion in 2020. Formaldehyde, acetaldehyde, and "others" (those not itemized in the figure) were the main HAPs emitted to the outdoors from residential combustion using oil in 2020. The biggest portion of HAP emissions to the outdoors from RWC in 2020 were acetaldehyde, formaldehyde, and "others." For other fuel types not shown here, formaldehyde was the main HAP emitted to the outdoors from residential combustion. These values are not weighted by their toxicity. This figure includes an inset showing the total outdoor HAP emissions from residential combustion for each fuel type, in absolute units (pounds), showing that RWC makes up nearly all the HAP emissions to the outdoors from residential combustion.

Figure 1. 2020 Relative Share of HAP Emissions to the Outdoors from Residential Combustion by Fuel Type



Data source: United States Environmental Protection Agency (2020)
Notes: Some of these data on residential combustion may include combustion with outdoor appliances like grills. Oil includes distillate oil and kerosene. "Other" fuels include bituminous coal and LPG. "Other" HAPs include the following (not a complete list): 1,3-butadiene, ethylbenzene, PAHs, xylenes, and metals like arsenic, cadmium, chromium, mercury, and nickel.

2.1.1 What gaps identified in the 2022 report regarding research on ambient air pollution and climate change impacts were supplemented by the updated literature review?

Listed below are the gaps we identified in the 2022 report regarding ambient air pollution and climate change impacts for which we found new literature in this addendum (we do not show the gaps for which we did not identify any new literature). We note where the literature reviewed in this new addendum supplements each gap, and then in the subsequent section we provide further details on the findings in the new literature.

- Gap from the 2022 report regarding **lack of inclusion of upstream emissions and lack of comprehensive lifecycle assessments**: *Of the few papers that did assess natural gas and the many that considered wood, none included any upstream emissions. We found no studies that presented a comprehensive lifecycle assessment of emissions, concentrations, or health impact from different fuels used for IRC. That is, the upstream component of fuels production, particularly petroleum fuels, is likely to be a significant emitter that should be addressed, potentially including HAP emissions from fuel extraction and refining processes. Although these occur outside the home, they are directly linked to IRC. The only study that discussed this specifically omitted these impacts. To relate upstream gas production directly to residential fuel consumption also would be challenging. CH_4 is a powerful GHG, but we found no studies on impacts including CH_4 leaks across the gas supply and distribution chain related to IRC.*
    - The literature reviewed in this addendum somewhat supplements this gap, specifically on CH_4 leaks; see Michanowicz et al. (2022), Lebel et al. (2020), and Sargent et al. (2021), discussed below. However, substantial gaps remain in analyses of natural gas-fueled IRC impacts on upstream emissions.
- Gap from the 2022 report regarding **sparse research on air quality impacts of natural gas-fueled IRC in general and secondary pollutant formation (ozone and secondary PM)**: *Wood clearly dominates PM emissions from IRC, but natural gas dominates the NOx emissions. We found only one study focused on the air quality impacts of natural gas-fueled IRC, considering only one state and focused on PM but excluding certain upstream effects. Ozone formation impacts should also be considered for a comprehensive ambient evaluation, as should emissions from electricity generation and secondary PM. The only study we found that did include gas consumption on photochemistry specifically excluded the IRC portion. One study considered secondary PM and focused on IRC of gas but excluded O_3 and was limited to a single state. We found only one study that did consider O_3. However, it did not separate IRC from other sectors to be decarbonized, and thus was not further reviewed. The magnitude of IRC NOx emissions compared to other sources, and the potential for O_3 impacts from NOx reductions must be considered, and the potential for enhanced spatially or seasonally varying impacts. More comprehensive, fuel-comparing evaluations are needed.*
    - The literature reviewed in this addendum somewhat supplements this gap, specifically on the air quality and climate change impacts of natural gas-fueled IRC; see Yang et al. (2025), Michanowicz et al. (2022), and Grobler

(2023), discussed below. However, substantial gaps remain in analyses of natural gas-fueled IRC impact on upstream emissions, ozone impacts and secondary formation, fuel comparisons, etc.

- Gap from the 2022 report regarding **lack of U.S.-centered studies and of analysis of disparate impacts and environmental justice concerns**: *Overall, while recent evidence of household air pollution contributing to outdoor air pollution and climate change is ample, much of the current literature focuses on developing world and dirtier fuels and technologies, such as cookstoves. Further research on U.S. emissions, air quality, and climate impacts on IRC is needed. This also includes any disparate or environmental justice impacts, for which only one study showing, but not elaborating on, disparities was found.*
    - The literature reviewed in this addendum somewhat supplemented this gap, specifically on the disparate impacts of natural gas leaks; see Weller et al. (2022), discussed below. However, substantial gaps remain in fuels and technologies most relevant to U.S. populations as well as analyses of disparate impacts and environmental justice.

2.1.2 Synthesis of relevant literature in this addendum on the topic of ambient air pollution and climate change impacts

Below we provide topical syntheses on the six references reviewed for this addendum which supplemented the evidence gaps noted above.

- **CH_4 leaks to the atmosphere related to IRC can be notable and can persist despite pipeline repairs.**

  Michanowicz et al. (2022) tested building natural gas appliance lines from building risers, and their findings suggested small leaks of natural gas persist in the distribution system, emitting CH_4 and HAPs to indoor and ambient air.

  Lebel et al. (2020) tested water heaters fueled by natural gas and found that storage water heaters emit most of their CH_4 to the atmosphere while the appliances were off (i.e., incomplete combustion by pilot lights, or other nearby pipe leaks).

  Sargent et al. (2021) noted that the Boston natural gas infrastructure (overall, not just residential) may lose 2.5% of its gas consumed to leaks, with a notable portion occurring at the residential site (i.e., related to the presence and usage of natural gas appliances), and replacement of leak-prone pipes has not improved that statistic.

- **Outdoor emissions of air pollutants and GHGs from natural gas appliances can vary in composition and amount by location and season and they may not be accounted for in common emission inventories. Reductions in those emissions**

from converting to electric appliances depend on the carbon intensities of local power grids and on local climate.

In Yang et al. (2025), the authors conducted ambient air quality experiments heating peanut oil with a natural gas stove and with an induction cooktop. When heating peanut oil and comparing to natural gas cooking, induction cooking led to reductions in outdoor emissions by 27% for VOCs, 100% for CH_4, 27% for $PM_{2.5}$ (with little effect on particle size distribution), 24% for ozone forming potentials, and 11% for CO_2 equivalent (CO_2e). These experiments used high-purity natural gas, and typical residential gas will contain more impurities leading to higher disparities in VOCs, for example.

Michanowicz et al. (2022) found that the chemical composition of leaks in residential distribution systems of natural gas can vary by season, geography, etc. Extrapolating out their measurements, they estimated several hundred kilograms of total benzene, toluene, ethylbenzene, and xylenes (BTEX) compounds may be emitted annually from natural gas CH_4 leaks in Boston and are not accounted for by common inventories like the EPA NEI.

Grobler (2023) used modeling to estimate the change in U.S. CO_2 emissions if all residential heating were converted to electric. Nationwide, the author estimated that a switch-out to air-source heat pumps would increase CO_2 annual emissions by 20%, while a switch-out to resistance heating would increase emissions by 130%, and a switch-out to electric ground-source heat pumps would decrease emissions in most areas. These calculations only included direct impacts (i.e., not upstream lifecycle impacts); they did not include wood combustion, and they used the projected electric grid for 2023 (whereas a more decarbonized grid would yield additional reductions in CO_2). The changes in emissions would vary geographically based on local carbon grid intensities and local climate.

- **Leaks to the atmosphere from natural gas pipelines have been observed to be disproportionately larger in areas with higher percentages of people of color and in areas with lower household incomes.**

  Weller et al. (2022), in a sample of U.S. metropolitan areas, found that leaks in the pipelines of natural gas tended to increase with increasing percent people of color and with decreasing household income. The statistically significant percent increases in leak density per a one standard deviation increase in percent people of color were 15% in Boston, 23% in Long Island, and 52% in Dallas. While most other metropolitan areas also showed increasing leak density per increasing percent people of color, the results were not statistically significant. For median household income, while most metropolitan areas showed increasing leak density per decreasing median household income, only one was statistically significant: in Long

Island, a decrease in income of $30,500 corresponded to an increase of 16% in leak density. Accounting for housing age made little difference in these relationships.

Beyond the six references synthesized above, we reviewed six additional references and determined that they did not address the evidence gaps noted above: four addressed RWC (Jiang et al., 2024; Noblet et al., 2024; Li et al., 2022; Marin et al., 2022) which was adequately addressed by references synthesized in the 2022 report, one addressed combustion units and fuels not likely to be widely used in the United States (Rönkkö et al., 2023), and one did not adequately draw conclusions about ambient air from IRC (Zusman et al., 2021). We also reviewed two other references (Eagles et al. (2024)[2]; Nassikas et al., 2024) which contained no primary data but directed us to some of the primary sources cited above.

2.2. Health Impacts of IRC

This section focuses on health impacts resulting from indoor and outdoor exposure to air pollutants generated by IRC. As detailed in the 2022 report, there is ample evidence that exposure to air pollution causes adverse impacts on health, particularly on respiratory outcomes. These detrimental health effects are experienced throughout the life-course (see Figure 2) but may differ for different pollutant sources. Therefore, we continue to stress that caution is warranted when using evidence on associations with detrimental health effects found for pollutants from one source to estimate impacts for the same pollutant from other sources (e.g., $PM_{2.5}$ from traffic and from IRC).

[2] The Eagles et al. (2024) report was identified as a recent potential seed study.

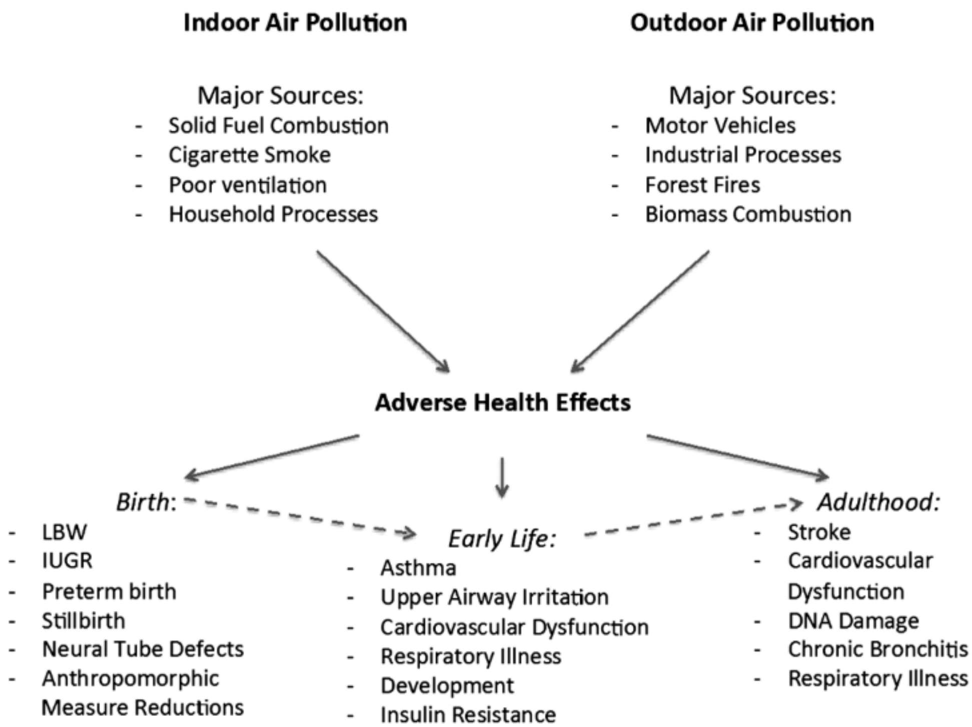


Figure 2. Summary of Adverse Health Effects from Exposure to Air Pollution

Source: Farmer et al. (2014)

2.2.1 What gaps identified in the 2022 report regarding research on health effects from indoor and outdoor exposure to IRC air pollution were supplemented by the updated literature review?

Recent studies reviewed in this addendum have partially addressed a few of the gaps identified in the 2022 report regarding health impacts from IRC due to exposure indoors and outdoors:

- *Limited evidence on health impacts of IRC from different sources in the United States.*
- *Lack of robust studies in terms of study design, selection of target population and sample size, exposure assessment, outcome assessment, control for co-exposures and potential confounders, etc.*

We note below where the literature reviewed in this new addendum supplements gaps, and then in the subsequent section (2.2.2), we provide further details on the findings in the new literature. We do not examine the gaps for which we did not identify any new literature.

- **Several recent US studies used prospective designs or interventions, which provide more robust evidence of associations between IRC and health**. Longitudinal designs were used in two US studies that linked indoor nitrogen dioxide (NO_2), $PM_{2.5}$ and the use of forced air systems to poorer respiratory outcomes in individuals with pre-existing health conditions (Carson et al., 2022; Kang et al., 2023). Another longitudinal US study suggested that cooking-related IRC may be adversely associated with child neurodevelopment (Grippo et al., 2023). Several recent US intervention studies examined the impact of improved cooking ventilation practices on air quality and child lung function in homes with gas stoves (Holm et al., 2024), or the impact of air cleaners on air quality and health outcomes in groups with pre-existing conditions (asthma and COPD; Gent et al., 2023; Raju et al., 2023) or households using wood stoves (Walker et al., 2022). **Persistent concerns** include the **modest sample sizes** in these interventions (N = 14 to 461), and that **sources of indoor pollutants were not always characterized** (Raju et al., 2023).
- **A few recent studies have strengthened exposure estimation by incorporating measures of IRC usage**. For example, a study of adults with asthma in Chicago used **time-activity patterns** to construct estimates of indoor exposure to several pollutants (Kang et al., 2023). In cross-sectional analyses of asthma control, associations with NO_2 and O3 were stronger using time-activity weighted indoor exposure vs. indoor concentrations. Recent **modeling efforts have also made advances towards estimating air pollutant exposures based on home characteristics that include appliance types and use**, along with measures of ambient indoor and outdoor pollutants (Zusman et al., 2021; Kirwa et al., 2024). Zusman et al. (2021) found that beyond presence of a gas vs. electric stove, cooking frequency and forced air ventilation were strongly predictive of indoor NO_2. Collecting adequate model input data to characterize potential pollutant sources – both indoors and outdoors – will be an important component of future research. A **persistent concern** is that in addition to improving model estimates, studies that **directly examine how health outcomes associate with appliance type and usage are needed** to better understand how IRC sources contribute to adverse health effects. A recent systematic review on gas cooking and child respiratory outcomes by Li et al. (2023) noted that most studies analyzed presence vs. absence of gas stoves: only one addressed cooking frequency, and one the use of forced ventilation.

- **Recent studies have also analyzed paired indoor and outdoor air pollutants as a step toward more holistically evaluating where harmful exposures may occur**. This includes two recent US studies – one a feasibility pilot on respiratory outcomes (e.g., Kang et al., 2023; Wi et al., 2023). Kang et al reported finding significant associations with indoor but not outdoor concentrations of NO_2 and $PM_{2.5}$, although the extent to which greater time indoors (an average of 70%) contributed to this finding is uncertain. While higher indoor NO_2 was associated with presence of a gas stove, cooking frequency was not characterized. A **persistent concern** is that **literature identifying the contribution of indoor vs. outdoor sources to either indoor or outdoor NO_2 is still lacking**.

2.2.2 Synthesis of relevant literature in this addendum on the topic of health effects from indoor and outdoor exposure to IRC air pollution

The 2022 report found evidence of associations between several IRC sources and health outcomes. However, evidence from studies conducted in the United States or similar contexts in the 2022 report was limited.

Recent literature reviewed for this addendum adds some evidence that IRC exposure may be associated with **respiratory outcomes**, however, **findings are heterogeneous, and conclusions are limited by methodological issues.** We provide a summary of evidence from this addendum here (and detail the findings in section 2.2.2.1 below):

- The literature reviewed in this addendum provided **mixed or limited evidence of associations with different respiratory outcomes**:
    - Mixed evidence for associations with **asthma-related outcomes**.
    - Mixed evidence for associations with **lower respiratory tract infections** (LRIs).
    - Limited evidence for associations with **chronic obstructive pulmonary disease** (COPD).
    - Mixed evidence for **other respiratory health outcomes**.
- The literature reviewed in this addendum provided **additional evidence of adverse respiratory outcomes associated with indoor NO_2 and/or gas cooking in children and adults** in the United States (e.g., Scott Downen et al., 2022; Gent et al., 2023; Kang et al., 2023).
- The literature reviewed in this addendum provided **additional evidence of adverse respiratory outcomes associated with frequent wood burning (Carson et al., 2022) and with indoor $PM_{2.5}$ in children and/or adults** in the United States (White et al., 2022; Kang et al., 2023); however, studies examining $PM_{2.5}$ did not link measurements to specific indoor sources. One study examining a population of

children and adults with cystic fibrosis found null associations between wood stove and fireplace use and measures of symptom exacerbation and lung function (White et al., 2022).

Studies on **non-respiratory outcomes have similar limitations, with the added drawback of an even smaller body of literature**. For example, a recent meta-analysis synthesized the impact on blood pressure of several indoor air cleaner intervention studies in five high-income countries, but the U.S. studies included did not discuss IRC sources (Faridi et al., 2023). More importantly, the small number of studies that examine how non-respiratory outcomes associate with indoor measures of air pollutants, or with well-characterized presence and use of IRC appliances, precludes conclusions. There is a need for more research. We detail the findings from studies reviewed for this addendum in section 2.2.2.2 below.

One meta-analysis reviewed in this addendum provided **additional information on health effects associated with indoor VOCs but did not link VOCs to specific sources** (Liu et al., 2022). No reviewed studies examined indoor ultrafine particulates (UFP) or nitrous acid (HONO).

The literature reviewed in this addendum provided some **additional evidence of adverse health effects in susceptible populations**, such children and individuals with asthma, obesity, or pre-existing conditions (e.g., Scott Downen et al., 2022; Kang et al., 2023; Radbel et al., 2024; Morishita et al., 2018; White et al., 2022).

The following subsections describe the findings from newly reviewed articles, with a focus on studies conducted in the United States. Findings are organized by health outcome (respiratory versus non-respiratory).

2.2.2.1 Respiratory health outcomes

We reviewed 17 additional studies with respiratory health outcomes published since the 2022 report, including 4 systematic reviews with meta-analyses, 3 reviews without meta-analyses, 5 observational epidemiologic studies, 3 intervention studies, and 2 modeling studies. These studies primarily focused on wood stoves, gas stoves, indoor NO_2, and indoor $PM_{2.5}$. Outcomes evaluated included **asthma development and/or exacerbation** (10 studies), **LRIs** (3 studies); **COPD** (2 studies); and **other respiratory outcomes** such as lung function, airway inflammation, and respiratory symptoms (5 studies).

Overall, the new studies provided **some additional evidence that exposure to IRC is associated adverse respiratory health outcomes in the U.S. in both children and adults, although evidence was mixed for some IRC sources**. Radbel et al. (2024) conducted a narrative review of indoor pollution and airway health focusing on studies from 2021-2024. These authors concluded that there is evidence of associations between indoor air pollution and a range of respiratory health outcomes, including the development and exacerbation of airway disease, decreased lung function, and respiratory symptoms. In that review, one of two recent studies that examined gas stove measures reported finding significant associations with poorer respiratory outcomes in adults. Two modeling studies estimated that gas stove use may be responsible for a substantial number of pediatric asthma cases in the U.S., with **one study estimating 200,000 current cases are attributable to gas and propane stoves** (Kashtan et al., 2024) and the other estimating 12.7% (95% confidence interval (CI): 6.2-19.3%) of current childhood asthma is attributable to gas stoves (Gruenwald et al., 2022). Meta-analyses conducted across multiple countries documented associations between gas fuels and respiratory outcomes (acute LRIs or pneumonia, COPD) when compared to cleaner fuels, between indoor NO_2 and asthma symptoms, and between indoor biomass burning and COPD. Observational epidemiologic studies documented mixed findings for exposures relating to wood burning and for indoor NO_2, with some studies observing adverse effects and others observing no association. Results from two intervention studies provided additional evidence of associations between indoor air pollutants and adverse respiratory health outcomes. However, none of the intervention studies found significant changes in measures of respiratory health associated with interventions aimed at reducing pollutants from gas and wood stoves.

Findings, strengths, and limitations of each study are discussed in further detail below.

Mixed evidence for associations between IRC exposures and asthma-related outcomes

Ten studies examined asthma development and/or exacerbation in relation to IRC exposures. Most of these studies focused on exposure to either indoor NO_2 or gas appliances, with some studies finding statistically significant associations with asthma-related outcomes and others finding null associations.

Indoor NO_2 and gas appliances: Four studies provided evidence of an association between indoor NO_2 concentrations and/or gas appliances and asthma-related health outcomes, including three studies that were conducted in the United States:

- In a meta-analysis of studies examining gas appliances and/or indoor NO_2 concentrations, de Mesquita et al. (2023) found statistically significant associations between indoor NO_2 concentrations and higher odds of asthma symptoms and between use of gas appliances and higher odds of asthma medication use. However, studies included in this review were conducted in multiple countries, including the United States.
- Gent et al. (2023) conducted a randomized, double-blind cross-over trial to investigate the influence of NO_2 scrubbing or particle filtration vs. sham air cleaning on asthma symptoms. This study was conducted among U.S. children aged 5 to 11 years with persistent asthma, living in homes with gas stoves, and household NO_2 of 15 parts per billion (ppb) or greater. NO_2 treatment reduced mean household levels

by 3.98 ppb vs. other arms. In an intent-to-treat analysis, neither NO_2-reducing nor particle-reducing treatment was associated with reduced asthma symptoms. However, higher measured household NO_2 was associated with increased symptoms (increase of 0.7 symptom-days in 14 days for every 10 ppb increase in NO_2). When stratified by measured household NO_2, symptoms were lowest in the particle-reducing arm, leading the researchers to suggest that future studies investigate how reducing both NO_2 and particle pollution influences asthma exacerbations.

- Scott Downen et al. (2022) conducted a pilot study of home-based NO_2 monitors among 30 pediatric asthma patients aged 5-21 years in the Washington, D.C. region. The frequency of NO_2 concentrations greater than 21 ppb measured over the six-day monitoring period was significantly associated with higher hospital admissions due to asthma over the 12 months prior to the monitoring period. While NO_2-emitting appliances were not directly examined in relation to health outcomes, the study documented higher NO_2 concentrations in homes with versus without gas stoves. However, this study has several limitations, including the small sample size, lack of adjustment for potential confounding variables and the measurement of the health outcome during a period time that occurred prior to the measurement of the exposure.
- Kang et al. (2023) conducted both cross-sectional and longitudinal analyses of the association between indoor air pollutants including NO_2 and asthma control among a small population of asthmatic adults in Chicago, IL (n=53 adults in 41 unique households). In cross-sectional mixed-effects models, indoor NO_2 was associated with significantly lower scores on the Asthma Control Test (ACT), a measure of asthma control. Indoor ozone was also significantly associated with lower ACT in single-pollutant logistic regression models, but this association was attenuated to non-significance in mixed-effect models accounting for other indoor pollutants and exposures. No significant cross-sectional associations were observed for other measured indoor air pollutants (formaldehyde, CO, CO_2, PM_1, PM_{10}) or for stove type (gas versus electric). In longitudinal analyses, indoor NO_2, PM_1, $PM_{2.5}$, and PM_{10} were significantly associated with lower ACT scores.

In contrast to the results from the studies described above, two studies did not find evidence of an association between either NO_2 or gas fuel use and asthma-related outcomes:

- In a feasibility study (N=62 families), Wi et al. (2023) examined how paired indoor and outdoor measures of NO_2 were associated with asthma symptoms among children with persistent asthma. This study was conducted in a mixed rural-urban Minnesota setting with high rates of pediatric asthma rated as having good air quality. Indoor/outdoor and winter/summer NO_2 measures were low (highest median for winter outdoor NO_2 = 3.9 ppb). In unadjusted models, associations with NO_2 were predominantly null for all measures of asthma exacerbation (daytime or nighttime asthma symptoms, rescue medication use, and asthma control status). Unexpectedly, despite lower NO_2 levels in summer (median 2.0 ppb), there were non-significant positive associations for outdoor summer NO_2 and all four asthma exacerbation measures. Further analysis to investigate the role of factors such as allergens was limited in this small feasibility study.

- Puzzolo et al. (2024) conducted a systematic review and meta-analysis of health outcomes associated with gas fuel use for cooking or heating across low, middle, and high-income countries and reported no significant associations between gas fuel use and asthma in either children or adults. However, significant associations were observed for other respiratory health outcomes. Specifically, gas fuel was associated with significantly higher odds of acute LRIs or pneumonia and COPD but lower odds of bronchitis when compared to use of cleaner fuels (e.g., solar, electric) in meta-analysis. When instead comparing gas fuels to other polluting fuels (e.g., wood, charcoal), gas fuel was associated with significantly lower odds of acute LRI or pneumonia, COPD, bronchitis, severe respiratory illness or death, pulmonary function deficit, cough, and wheeze. The relevance of these results to the U.S. is unclear; however, it is worth noting that conclusions regarding asthma outcomes did not vary when stratified by country income level.

Two modeling studies (Kashtan et al. 2024, Gruenwald et al. 2022) estimated the number or fraction of cases of pediatric asthma due to gas stoves in the United States:

- Kashtan et al. (2024) used new field measures to construct and validate a population model of NO_2 exposure from gas and propane stoves in the United States, accounting for housing characteristics and use patterns (e.g., residence size, cooking time, range hood use). On average, estimated maximum daily hour-average NO_2 from median gas and propane use exceeded 200 µg /m^3 (~100 ppb volume (ppbv)), the World Health Organization's (WHO) 1-hour indoor exposure guideline, on 12 days (3.3% of days) per year, increasing to ~110 days per year for home cooks in the 95th percentile of stove use. Stove-attributable NO_2 also exceeded the EPA's outdoor standard of no more than 2% of days with maximum NO_2 above 100 ppbv. By combining the model with data from the Residential Energy Consumption Survey (RECS) survey and a meta-analysis of long-term NO_2 and pediatric asthma (Puzzolo et al., 2024), the authors estimated that gas and propane stoves are responsible for 200,000 current cases of pediatric asthma, roughly 10% of the number attributable to road traffic. The authors also estimated, based on findings for outdoor NO_2, that gas and propane stoves may be responsible for up to 19,000 U.S. adult deaths annually. Findings also demonstrated variability in stove-related NO_2 exposure associated with behaviors and use.

- Using results from previous meta-analyses and survey data on the prevalence of indoor gas stoves, Gruenwald et al. (2022) quantified the population attributable fraction for current asthma among children associated with gas stove use in the United States. They estimated that 12.7% (95% CI 6.3-19.3%) of current childhood asthma is attributable to gas stove use. Due to the varied prevalence of children living in homes with gas stoves, among the 9 states for which data were available, the estimate of gas stove-attributable asthma burden was highest in Illinois (21.1%) and lowest in Florida (3%). The authors used data from the 2019 American Housing Survey (AHS) and an effect estimate from a meta-analysis of the association between gas stoves and current childhood asthma from 10 studies in North America and Europe (Lin et al. (2013) meta-analysis: odds ratio (OR) = 1.34, 95%CI = 1.12–1.57). However, studies in the Lin et al. (2013) meta-analysis were not limited to the United States, and results from a secondary analysis limited to six studies conducted in North America were not statistically significant (OR = 1.12, 95% CI = 0.73, 1.73).

Other IRC exposures: Two studies examined asthma-related health outcomes in relation to other IRC exposures:

- **VOCs:** Liu et al. (2022) conducted a systematic review and meta-analysis of indoor VOCs and several health outcomes including asthma, bronchitis, and rhinitis. In meta-analyses, several VOCs – including benzene, toluene, xylene, acetaldehyde, p-dichlorobenzene, and tetrachloroethylene – were associated with a significantly higher risk of asthma. The study also included meta-analysis of associations between benzene and bronchitis and between benzene, toluene, and xylene and rhinitis; however, none of these associations were statistically significant. **The relevance of these results to the United States is unclear**, as information on the countries in which studies were conducted was limited. While the focus on the health effects of VOCs addresses a gap identified in the 2022 assessment, it is important to note that **it is not clear whether or to what extent IRC contributed to the exposures in the meta-analyzed studies.**
- **Indoor biomass burning:** Holtjer et al. (2023) conducted an umbrella review of previously published systematic reviews and meta-analyses of environmental and lifestyle risk factors for adult onset-asthma and COPD. 15 reviews provided evidence of an association between indoor biomass burning and COPD, while no reviews identified indoor biomass burning or other IRC exposures as risk factors for adult-onset asthma. **The relevance of these results to the United States is unclear**, as most reviews were stated to focus on low-income countries.

Mixed evidence for associations between different IRC exposures and LRIs

Three studies examined associations with LRIs including pneumonia and bronchitis. Each study examined a different IRC exposure:

- **Wood stoves and indoor $PM_{2.5}$:** Walker et al. (2022) conducted a three-arm randomized trial to examine the air pollution and child health impacts of two different interventions on rural households using wood stoves. Participating households were located in Alaska, Montana, and the Navajo Nation (Arizona and New Mexico) and were divided into three groups – one receiving an educational intervention, one receiving an air filtration intervention (provision of a portable air filtration unit), and one constituting the control group. The outcomes of interest were indoor $PM_{2.5}$ concentrations and LRIs among children under the age of 5. There were no significant differences in either indoor $PM_{2.5}$ concentrations or in LRIs between the intervention and control groups. However, indoor $PM_{2.5}$ concentrations were significantly associated with higher odds of LRIs.
- **Gas fuel:** Puzzolo et al. (2024) found that gas fuel use was associated with significantly higher odds of acute LRIs or pneumonia but significantly lower odds of bronchitis when compared to the use of cleaner fuels (e.g., solar, electric) in a meta-analysis. However, gas fuels were associated with significantly lower odds of both outcomes when compared to other polluting fuels (e.g., wood, charcoal).
- **VOCs:** Liu et al. (2022) found no significant association between benzene and bronchitis in a meta-analysis of indoor VOCs and health.

Limited evidence of associations between IRC exposures and COPD

Two studies, both of which included data from countries other than the United States, reported evidence of an association between different IRC exposures and COPD:

- **Gas fuel:** Puzzolo et al. (2024) found that gas fuel use was associated with significantly higher odds of COPD when compared to use of cleaner fuels (e.g., solar, electric), and with significantly lower odds of COPD when compared to other polluting fuels (e.g., wood, charcoal) in meta-analyses.
- **Indoor biomass burning:** Holtjer et al. (2023) identified 15 reviews providing evidence of an association between indoor biomass burning and COPD.

Mixed evidence for other respiratory health outcomes associated with IRC exposures

Six studies examined associations between IRC exposures and other respiratory health outcomes:

- A narrative review of studies on indoor air pollution and airway health in high-income countries published from 2021 to 2024 (Radbel et al., 2024), cited two studies on **respiratory outcomes and presence of a gas stove**. In one cross-sectional pan-European study, **self-reported shortness of breath** at rest and self-reported wheeze with breathlessness was associated with gas vs. electric stove use.

Associations were stronger with those who spent more time cooking, those who rarely opened windows, and those who used bottled vs. service line gas, but not among those with asthma. However, associations with diagnosed airway diseases were not examined. In the second study, a cross-sectional analysis of Danish adults, adjusted associations with lower forced expiratory volume over one second **(FEV1)** were significant for ambient outdoor NO_2 but not for gas stoves. Indoor NO_2 was not measured, and while use of a vent hood was considered, cooking frequency was not characterized.

- **Wood stove and fireplace exposure, cystic fibrosis exacerbation, and lung function:** Carson et al. (2022) examined the association between exposure to several indoor air pollution sources and lung function, all-cause hospitalization, and pulmonary exacerbation over four years of follow-up of children and adults with cystic fibrosis in the U.S. Among both children and adults, no significant associations were observed between wood stove or fireplace exposure and any of the outcomes. However, exposure to forced air was associated with a significantly lower annual rate of FEV1 percent predicted change among children only. A limitation of this study was the use of self-reported measure of exposure (any versus no exposure to each air pollution source).
- **RWC, lung function, and airway inflammation:** White et al. (2022) examined the association between RWC and measures of lung function (forced expiratory volume in one second (FEV1), forced vital capacity (FVC), FEV1/FVC) and inflammation (fractional exhaled nitric oxide ([FeNO)]) among adults participating in an asthma case-control study in the United States. Frequent wood burning was associated with significantly higher FeNO among all study participants and with significantly lower lung function among individuals with asthma only. A limitation of this study was the use of self-reported measures of exposure (frequent or some exposure to wood burning versus no exposure).
- **Gas stoves, indoor air pollutants, and lung function and inflammation**: Holm et al. (2024) conducted a pilot study of a cooking ventilation intervention at 14 homes in the San Francisco Bay Area that each had a gas stove and either a venting range hood or an over-the-range microwave/hood. Partway through the study period, participants received an educational intervention on the health impacts of cooking-related pollution and on strategies for reducing pollution (e.g., using the range hood, using back burners). Following the intervention, homes had higher use of intervention-recommend strategies and lower NO_2 and $PM_{2.5}$ emissions, but there were no statistically significant changes in lung function or lung inflammation among children. However, the small sample size may have limited the sensitivity of the study to detect an association.

- **Gas fuel and multiple respiratory outcomes:** Puzzolo et al. found that gas fuel use was associated with significantly lower odds of severe respiratory illness or death, pulmonary function deficit, cough, and wheeze when compared to other polluting fuels (e.g., wood, charcoal).
- **VOCs and rhinitis:** Liu et al. (2022) found no significant associations between several indoor VOCs (benzene, toluene, and xylene) and rhinitis.

2.2.2.2 Non-respiratory health outcomes

This section includes findings on cardiovascular health, neurological outcomes, and other outcomes (all-cause mortality and reproductive health).

Cardiovascular health outcomes

A small body of literature has examined associations between cardiovascular outcomes and indoor air pollutants at levels relevant to U.S. populations. However, the specific contribution of IRC sources to indoor air pollution in these studies is uncertain, and evidence remains limited and mixed.

Several studies have reported associations between indoor air pollution and blood pressure (BP), with some evidence of adverse effects in vulnerable groups. The 2022 report cited a New Orleans study that found indoor BC to be associated with increased systolic blood pressure (SBP), particularly among hypertensive individuals, but sources of indoor BC were not characterized (Rabito et al., 2020). In a 2021 systematic review of air cleaner interventions affecting indoor $PM_{2.5}$ (Cheek et al., 2021), only six of 10 studies reported significant beneficial changes in BP. However, one of these was a U.S. intervention in which reductions in SBP were most apparent in obese participants (Morishita et al., 2018). Other interventions reporting significant BP reductions were conducted in China.

Additionally, a 2023 meta-analysis (Faridi et al., 2023) reported that **evidence of beneficial effects of portable air cleaner (PAC) interventions on BP was strongest in settings with lower indoor $PM_{2.5}$.** For studies with baseline $PM_{2.5}$ below 25 µg/m^3, the pooled effect estimates included significant reductions of both SBP [- 4.84 mmHg (95 % CI: -9.23, -0.45)] and diastolic blood pressure (DBP) [-1.82 mmHg (95 % CI: -3.56, -0.09)]. There was little evidence of BP effects in studies with higher baseline $PM_{2.5}$ (pooled estimates -0.27 (95% CI -1.55, 1.01) and -0.15 (95% CI -1.05, 0.74) for SBP and DBP, respectively). Pooled estimates indicated larger BP reductions in interventions conducted in North America and Europe [N=5 studies including 2 in the U.S., SBP -2.95, (95% CI -6.01, 0.10)] than in Asia [N=12, SBP (-1.95, 95% CI -4.57, 0.66)]. However, the U.S. studies included in these reviews were conducted in households near highways, and traffic may have been the major source of $PM_{2.5}$. **Evidence linking BP with other indoor pollutants besides $PM_{2.5}$. is lacking, as is evidence linking IRC sources of air pollution to hypertensive measures**.

Direct evidence linking indoor air pollutants from IRC sources to other cardiovascular outcomes is also limited. A systematic review on air cleaner interventions (Cheek et al.,

2021) included one intervention in a woodsmoke impacted community in Canada (about half the participants used a wood stove) that found beneficial effects of active air cleaning on endothelial function as measured by increased reactive hyperemia index. Evidence is needed for other IRC sources, and from additional studies.

A 2023 study of **U.S. adults with COPD added to the limited evidence of cardiovascular risks from indoor air pollutants among vulnerable individual**s (Raju et al., 2023). Indoor $PM_{2.5}$ (mean 13.8 ±2.45 µg/m^3) was associated with impaired cardiac autonomic function based on heart rate variability measures. Associations were also strongest among obese individuals. This study, which included an intervention, also found that participants randomized to active vs. sham air cleaning had significantly improved real-time changes in heart rhythms (root mean square of successive differences (RMSSD) between normal-to-normal intervals, 25.2% [95% CI, 2.99 to 52.1]). However, sources of indoor $PM_{2.5}$ were not described.

Among healthy individuals, a small study (n=20) in Italy suggested that indoor VOCs may affect cardiac autonomic function during sleep (Carandina et al., 2024). Total VOC levels, higher in households using gas vs. induction stoves (902 ± 434 vs 598 ± 217 µg/m^3), were associated with a greater number of cyclic variations in heart rates during sleep as measured by electrocardiogram. This study did not measure specific VOCs, and measures were obtained in living rooms rather than in sleeping areas. However, a California study (Kashtan et al., 2023) found significantly increased bedroom concentrations of the VOC benzene in homes with gas and propane vs. electric stoves, including several hours after stoves were turned off.

With few new studies, there is a paucity of evidence relating IRC-related indoor air pollutants and cardiovascular health in the U.S. **The limited literature suggests further study is warranted in contexts with low indoor** $PM_{2.5}$**, and particularly studies examining cardiovascular outcomes in vulnerable groups.** Studies to date have examined relatively few outcomes, although a wide range of cardiovascular outcomes have been related to air pollutants. Importantly, in studies that involved indoor pollutant measures as well as in air cleaning interventions, there was **inadequate information to determine whether IRC was an important source of pollution**.

Neurological outcomes

Despite mounting evidence in low- and middle-income countries, **in the earlier report no literature had been found on the potential impact of indoor air pollutants from IRC on children's neurodevelopment in high-income countries. One recent U.S. study addressed this gap,** reporting that prenatal or childhood exposure to any "unclean cooking fuel" – defined as natural gas, propane, or wood combined relative to electric appliances – was associated with poorer developmental outcomes through age 36 months (Grippo et al., 2023). Developmental outcomes were measured by parental ratings using the Ages and Stages Questionnaire. Exposure to any unclean cooking fuel was associated with significantly higher odds of failing to meet U.S. norms for any domain (OR, 95% CI = 1.28, 1.07-1.53), the gross developmental domain (1.52, 1.09-2.13), and the personal-social development domain (1.36, 1.00-1.85). Associations were not statistically significant for other domains (fine motor, communication, problem solving). In contrast, there was no evidence of associations with exposure to any unclean heating fuel (including natural gas, wood burning stove, pellet stove, wood fireplace, gas fireplace, coal). An **important limitation of this study is that the authors did not report associations with individual cooking fuels**, making it uncertain whether patterns of association were similar for gas vs. propane/wood exposure. Levels of indoor air pollutants were not quantified, and cooking frequency was not characterized. In addition, although the authors adjusted for socioeconomic variables associated with cooking fuels (e.g., parental education, insurance status), residual confounding is a potential concern given the strong relationship between cooking fuels and available socioeconomic variables (e.g., $p<0.0001$ for differences in fuel types and maternal and paternal education).

Grippo et al. (2023) suggests further investigation of indoor air pollution sources and child development is warranted in high-income countries. Parsing effects from those of outdoor pollutants will be important, given growing evidence in high-income areas that ambient air pollution may influence child development (Ha, 2020; Shang et al., 2020).

Other health outcomes (all-cause mortality and reproductive health)

A large body of literature links **ambient exposure to pollutants such as NO_2 and $PM_{2.5}$ with all-cause mortality** (e.g., de Bont et al. (2022)). In some cases, estimates of mortality associated with these air pollutants have been based on meta-analyses that excluded studies on indoor exposures (e.g., Orellano et al. (2020); de Mesquita et al., 2023). Unfortunately, **evidence specifically examining mortality associated with indoor air pollutant exposures in high-income countries is lacking**.

Recent systematic reviews have examined associations between **adverse pregnancy outcomes** and domestic use of gaseous fuels or wood for cooking and heating (Puzzolo et al., 2024; Luo et al., 2023). Studies on gaseous fuels in these reviews were all conducted in low- and middle-income countries. However, one study in New England reported an increased odds of **small-for-gestational age birth** (OR, 1.81 (95% CI, 0.96-3.38) associated **with wood stove use** (Fleisch et al., 2020). Further study is needed to replicate and quantify these wood fuel exposures, and to examine whether there are adverse pregnancy outcomes associated with indoor sources of gaseous fuels exposure in the United States.

3 Discussion and Limitations

Our conclusions should be viewed in the context of limitations of this research effort, which are similar to those discussed in the 2022 report. Also, this addendum focuses on findings from a systematic literature search update on only two of the research areas of interest considered in the comprehensive review summarized in the 2022 report. Thus, potential updates on the remaining research areas were not considered when developing this report. Also, gray literature sources were not included as the literature search update targeted peer-reviewed literature only.[3]

As mentioned in the 2022 report, peer-reviewed literature on health effects of exposure to IRC has largely targeted low- and middle-income countries (LMIC), and **the number of studies focusing on the United States** that examined IRC-related health effects **continues to be very small**.

Most studies that targeted indoor air pollutants **continue to not be specific to combustion sources or** not report associations between exposure to air pollutants generated by IRC and **specific health effects.**

- For example, the narrative review conducted by Radbel et al. (2024) **illustrates two key issues that limit conclusions for respiratory outcomes**.
    - First, **few studies using pollutant measures characterized the sources of pollution**. It therefore remains uncertain whether any associations are due to indoor vs. ambient sources of those pollutants.
    - Second, **few new studies examined associations between diagnosed health outcomes and either use of IRC appliances or indoor pollutant measures identified as coming from known, specific IRC sources**. There is a need for studies that jointly examine how well-characterized respiratory outcomes are associated not only with indoor pollutant measures, but also with well-characterized use of IRC appliances.
- Regarding **non-respiratory outcomes,** there are **too few studies** that examine associations with indoor measures of air pollutants, or with well-characterized presence and use of IRC appliances, as noted above for the meta-analysis conducted by Faridi et al. (2023).

Two additional modeling studies reviewed for this addendum estimated the number or fraction of cases of pediatric asthma due to gas stoves in the United States. However, as before, **we did not review any studies examining the health impact of IRC from all sources considering exposures both indoors and outdoors**.

Moreover, given the resources available for this project, **we reviewed a small fraction of the retrieved literatur**e, targeting articles that addressed the impacts of IRC in the United States. As done for the 2022 report, we used a combination of automated screening methods and manual screening methods to identify the articles most likely to be relevant for this analysis. Like before, although some of the pertinent articles (possibly affecting our conclusions) may have been missed**,** we believe that use of pre-screening prioritization

[3] Exceptions include gray literature identified as recent potential seeds and gray literature cited prominently in the 40 full-text review articles.

tools and LLM prompts for automated prioritization purposes has helped minimize this issue (see Appendix A for details).

Similar to the 2022 review, **study quality assessment was not in the scope of this project**, and, as such, the reviewed articles were not evaluated with respect to the quality of data and methods, including risk of bias, and potential conflict of interest. The focus on peer-reviewed references aimed to help ameliorate this issue.

The large volume of materials collected but not assessed in this report could be added to the previous collection and explored as part of a future systematic review. Furthermore, although quantitative synthesis and generation of new estimates based on the reviewed studies was beyond the scope of this project, there continues to be potential for a future research effort to leverage these findings through modeling approaches and generate new insights into impacts from IRC sources in the United States.

4 Recommendations for Future Research

Our recommendations for future work are similar to those included in the 2022 report. We have expanded some aspects here keeping them organized around the same *three lines of research requiring progressively larger amounts of implementation resources: (1) extensions of the current review, (2) quantitative synthesis of existing information, and (3) research requiring new data collection*.

4.1. Extensions of the current review

As noted in Appendix A, 8,168 unique article references were obtained from the bibliographic database searches during the addendum effort. After removing 3,067 references containing only foreign country or city terms in the title and abstract, ICF applied additional pre-screening prioritization tools to the remaining 5,101 potentially relevant studies. Out of this pool, ICF only manually screened 160 studies and reviewed full text for 40 studies. Gray literature sources were only included when identified as seed studies.

As mentioned in the 2022 report *to further improve robustness of our conclusions regarding IRC sources and impacts in the United States, and with the new knowledge of the volume of literature available, **these article collections may be explored as part of a systematic review***. Additionally, *another extension of the current review is **to implement a study quality assessment**, to further understand the robustness and applicability of the studies that underlie our conclusions*.

4.2. Quantitative synthesis using existing data

The 2022 report noted **possible modeling activities using existing data that could enhance assessments of the impacts of IRC emissions on outdoor air quality in the**

United States, which may be extended to the resulting health impacts. We do not repeat those recommendations here in the addendum, but we elaborate further on some aspects of study design. Also, we note the continued relative lack of data on BC emissions from IRC (particularly RWC) and the implications of those emissions on climate change.

We also highlight that Section 2.2 of the 2022 report presented IRC emissions data on CAPs and HAPs which may be leveraged as part of such modeling work. To estimate emissions to the outdoors, that information on IRC emission factors may be combined with information on consumer appliance usage and information on home ventilation. Also, as detailed in the 2022 report, several studies have applied different source apportionment methods to determine the contributions of different emission sources to $PM_{2.5}$ and PAHs ambient concentrations and estimate health impacts. Alternatively, existing inventories of outdoor emissions from IRC (e.g., the EPA's NEI) may be sufficient if they consider the IRC contribution, except in cases where results are needed by specific types of appliances.

Local-scale modeling (e.g., with EPA's AERMOD model) could utilize site-specific information where available to provide IRC outdoor air quality results at the neighborhood or city scale, while national-scale modeling could provide the bigger picture (similar to EPA's AirToxScreen). Atmospheric chemistry models (e.g., GEOS-Chem, CMAQ) could simulate formation of secondary pollutants (CMAQ and AERMOD are used for AirToxScreen). In fact, the results of EPA's AirToxScreen (which is produced annually, relying largely on the NEI) may be sufficient to understand the scale and scope of IRC impacts on outdoor air quality on county to national scales—again, as long as the residential combustion emissions estimated in the NEI (which do not differentiate uses/appliances) are sufficient for one's research purposes. Note that AirToxScreen is a screening-level assessment with limitations on what questions it can be used to answer.

Modeling of the impacts of appliance switch-out due to electrification would involve assessing the current and predicted future characteristics of the electrical grids across the country (which may be sufficiently available from the EIA) in order to characterize the power-plant emissions that would result from the switch-outs. Such emissions would have local and regional implications on air quality and human health.

The results of such air quality modeling could then be paired with human health benchmarks to estimate health impacts of IRC emissions to the outdoors. As noted in the 2022 report, EPA's BenMAP model may be useful for this purpose.

4.3. Research requiring new data collection

The 2022 report noted numerous possible areas of new data collection to strengthen the evidence on the impacts of IRC on outdoor air quality and climate change and on human health (from indoor and outdoor exposures), including data to:

- Improve our understanding of emissions and indoor air pollution from IRC sources in the United States.

- Support lifecycle assessment of climate and health benefits of existing and emerging fuel alternatives.
- Improve robustness and generalizability of research studies on health impacts from IRC.

We do not detail each of those recommendations, however, we note that the supplemented research synthesis in this addendum still left notable gaps in our understanding, such as:

- The quantities and locations of leaks in the distribution system of residential natural gas. Research synthesized in this addendum suggested these fugitive emissions may not be accounted for in existing inventories of outdoor emissions (e.g., the NEI) and may be of notable quantities.
- The quantity of BC emitted from IRC (all fuel types though particularly wood). The global warming potential of BC is more difficult to determine than for GHGs, and BC is not included in the U.S. GHG inventory.
- A more complete assessment of IRC impacts also would attempt to estimate the lifecycle impacts of IRC and of electrification switch-outs—following the fuels upstream from fuel distribution to refining and back to initial resource extraction. This would require estimating the portion of those upstream resource extraction, refining, and distribution emissions solely related to IRC or electrification switch-outs.
- According to Li et al. (2023), who conducted a systematic review of 66 studies on gas cooking and childhood respiratory diseases, study quality limitations persist in the literature, including imprecise definitions of exposure to gas cooking (as well as lack of prospective designs and limited adjustments for confounding variables). Although this topic was not examined in this addendum, we expect that limitations in indoor exposure data extend to other gas appliances, given that the 2022 report indicated a need for *new data collection for emissions and generated indoor air concentrations from gas-powered clothes dryers and water heaters, emissions from gas heating in general, and indoor air concentrations from gas fireplaces specifically*.
- New models could be developed to strengthen estimates of the contribution of IRC use to indoor and outdoor pollutant exposure.
- Building on existing studies with indoor pollutant estimates based on highly detailed information on IRC appliances and use, such as Zusman et al. (2021), there is an opportunity for research that analyzes associations between health outcomes and multiple exposure variables that can strengthen the current evidence base. This includes potential analyses relating a broader array of outcomes with: estimated paired indoor and outdoor concentrations; estimated indoor exposures based on time indoors; and IRC appliance variables constructed based on type, number, and frequency/duration of use.

5 References

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Appendix A. Research Methodology

This section summarizes the research methods used to assemble information for this review. Section A.1 describes the process employed to retrieve articles for review, along with the statistics on the number of articles obtained from various sources. Section A.2 summarizes automation methods used to improve the efficiency of the review process at various stages. The manual review approach (title/abstract screening and full-text review) and results are described in Section A.3. Section A.4 escribes additional data sources of information that have been consulted to support this review. Sections A.5 and A.6 provide details of the search strings and screening guidelines employed, respectively.

A.1. Article Retrieval

A.1.1. Search Scope

The initial collection of articles for review was compiled by implementing a search with the following scope:

- Bibliographic search platforms:
    - PubMed (NLM, 2025b) – an engine to search the MEDLINE (NLM, 2025a) collection of biomedical research articles from peer-reviewed sources assembled by the National Library of Medicine (NLM), National Institutes of Health, as well as other non-Medline literature submitted by publishers to NLM. PubMed searches titles and abstracts of the articles, as well as Medical Subject Heading (MeSH) terms assigned to indexed records;
    - EBSCOhost (EBSCO, 2025) – a platform to search multiple databases with peer-reviewed content licensed from reputable publishers. EBSCO searches various fields, including titles and abstracts;
    - Google Scholar (Google, 2025) – an engine to search a range of scholarly literature sources, such as peer-reviewed journals, technical reports, working papers, dissertations, books, etc. The full list of sources crawled by Google Scholar is not publicly available. Google Scholar searches articles full text and meta-data, which generally produces large results sets.
- Articles published between 2021 and January 2025;
- Articles in the English language; and
- Articles pertaining to the United States.

A.1.2. Query Development

For article retrieval, we used topic-specific queries represented by complex Boolean expressions combining multiple types of terms. The search terms and their combinations were developed based on topic definitions, using synonyms developed with input from the American Lung Association and topic subject matter experts. Because this was an update of the search conducted in 2022, we used search terms and sets developed for the previous search, with a few supplemental terms added and several search sets removed or slightly adjusted to reflect the shift in focus for this update. Topic subject matter experts and the client identified a small set of recently published relevant articles (i.e., positive seeds) that we used to validate queries (i.e., the queries were tested to ensure that the results contained the majority of the seed articles).

The queries have also been customized for the search platform as follows:

- We have expanded the topic-specific queries using select terms from PubMed's Medical Subject Heading (MeSH) controlled vocabulary thesaurus;
- For Google Scholar searches, each query has been translated into a set of search strings, with each string under 256 characters long (the maximum query length in Google Scholar). In that, the disjunction of the query-specific search strings has been confirmed to produce the original Boolean expression for the query.

Table 2 summarizes the general structure of the queries, with 2025 revisions of the queries used by the 2022 search identified in red. This search update is organized around two of the six topics originally covered by the 2022 search (topics 4 and 5) and addresses two research areas of interest to the 2025 update (research area #3 and research area #4). Table 5 contains the fully specified queries for each topic, their definitions, and their adaptations to the bibliographic database searched.

Table 2. Topic-Specific Query Structure

Research Area	Topic Definition	Query Identifier	Query Definition*	*Changes for 2025*
Research Area #3: Contribution of IRC to outdoor air pollution and climate pollution including GHGs	**Topic 5**: Contribution of indoor residential combustion to OAQ and GHG	5a	({Appliances} OR {Source}) **AND** ({Indoor Air Quality} **AND** {Outdoor Air Quality}) **AND** {Source Qualifier}	No change
		5a alt	*({Appliances} AND {Source})* ***AND*** *({Indoor Air Quality}* ***AND*** *{Outdoor Air Quality})* ***AND*** *{Source Qualifier}*	*Not used – subset of 5 only needed if results too large*
		5b	({Appliances} OR {Source}) **AND** {Air Quality General} **AND** ({Source Qualifier} OR {Action} OR {Exposure Reduction}) **AND** {Type}	No change
		5b alt	*({Appliances} AND {Source})* ***AND*** *{Air Quality General}* ***AND*** *({Source Qualifier} OR {Action} OR {Exposure Reduction})* ***AND*** *{Type}*	*Not used – subset of 5 only needed if results too large*

Research Area	Topic Definition	Query Identifier	Query Definition*	*Changes for 2025*
Research Area #4: Health impacts of indoor and outdoor exposure to IRC pollutants	**Topic 4**: Health impacts of exposure to IRC	4a	{Indoor Air Quality} **AND** {Type} **AND** {Health Impacts} **AND** {Review Study}	No change
		4b	{Indoor Air Quality} **AND** {Type} **AND** *{Health Impacts}* **AND** {Exposure Reduction}	*Health Impacts added to incorporate focus of former 4c*
		4c	*{Indoor Air Quality}* ***AND*** *{Type}* ***AND*** *{Exposure Reduction}* ***AND*** *{Health Impacts}* ***AND*** *{Modeling}*	*Eliminated (covered by 4b; Modeling is subset of 4b)*
	Topic 6: *Contribution of IRC to public health burden of OAQ or climate change*	*6a*	*{Indoor Air Quality}* ***AND*** *{Outdoor Air Quality}* ***AND*** *{Type}* ***AND*** *{Health Impacts}* ***AND*** *{Review Study}*	*Eliminated (subset of 4a)*
		6b	*{Indoor Air Quality}* ***AND*** *{Outdoor Air Quality}* ***AND*** *{Type}* ***AND*** *{Health Impacts}* ***AND*** *{Exposure Reduction}* ***AND*** *{Modeling}*	*Eliminated (subset of 4b)*

Abbreviations: IRC – indoor residential combustion; IAQ – indoor air quality; OAQ – outdoor air quality; GHG – greenhouse gas; alt – alternative

Notes: *Content within braces included in the Boolean expressions indicates concepts searched by the query. Each concept is represented by OR-ed terms used to represent it. For example, {Health Impacts} corresponds to OR-ed terms expressing potential health outcomes, such as "asthma," "respiratory" etc. Full search strings that spell out the concept definitions are provided in Section A.5. The 2025 revisions of the queries used by the 2022 search are identified in red.

A.1.3. Search Implementation

The final database searches were implemented in January 2025 and February 2025. Additional research performed after these dates are included in "ad hoc" findings.

A.1.3.1. Bibliographic Search Platforms

Below are the additional details on the execution of the searches on each bibliographic platform in our scope (topic numbers refer to the original scheme defined in Table 2):

- PubMed web interface has been used for reference retrieval. Topic 4 (health impacts of IRC) search that focused on reviews (Query 4a in Table 2) has been restricted to review articles in PubMed, to target the search better;
- The EBSCOhost web interface has been used for reference retrieval. The searches excluded MEDLINE, which is duplicative of PubMed, but otherwise were not restricted to particular databases. References were further restricted by Publication and Document Type to academic articles and journals;
- Google Scholar searches have been conducted using SerpAPI service (SerpAPI, 2025). For each search string, we have retrieved the top 20 references, which corresponds to the set of

results from the first page returned for a Google Scholar query via the web interface. This cutoff has been determined via Google Scholar query testing;

- Because Google Scholar does not retrieve full abstracts, we have used the Paperpile reference management service (Paperpile, 2025) to automatically extract full meta-data for the result set whenever possible. Full meta-data, including abstracts, have been obtained for approximately 95% of the references retrieved by Google Scholar;
- Following the use of Paperpile to extract full meta-data for Google Scholar results, ICF refined the Google Scholar results by applying the search strings to the title and abstract fields only. By default, Google Scholar searches the full text of sources. Because PubMed and EBSCO search titles and abstracts only, this additional step better aligned the Google Scholar search results with the PubMed and EBSCO search results.

All search results have been imported into EndNote (Clarivate, 2025). This tool has been used to remove multiple versions of the same reference within each topic. Table 3 summarizes the results of retrieval by topic (as performed using the original topic definitions).

Table 3. Results of Retrieval by Topic Area, Query, and Bibliographic Search Platform

Topic Definition	Query Identifier	Number of Retrieved References			Number of Unique References
		PubMed	EBSCO	Google Scholar	
Topic 4: Health impacts of exposure to IRC	4a	1,926	504	555	2,448
	4b	833	1,519	1,616	2,996
Topic 5: Contribution of indoor residential combustion to OAQ and GHG	5a	1,219	306	1,626	2,775
	5b	2,160	724	2,130	4,342

Notes: There is some duplication of references across the various searches (e.g., same reference found by one or more searches). A total of 8,168 unique references were found from all combined bibliographic platforms.

A.1.3.2. Gray Literature Sources

This search update did not include a gray literature search component.

A.1.4. Search Augmentation

The collection of article references retrieved via search has been supplemented in the following ways:

- Review of references cited in selected full-text review articles (see Section A.3.2);

- Articles added by subject matter experts post hoc, to support narrative development. These articles may have been discovered via searches but not reviewed as part of the “primary set” of screened articles.

A.2. Automated Screening

Although this search produced fewer results than the 2022 search due to the inclusion of more recently published literature and fewer topics, the search update still identified over 8,000 unique references. Because this project was not intended as a systematic literature review (i.e., a review of all retrieved articles), we planned to review a subset of prioritized references retrieved by the search. To focus our efforts on the most pertinent materials, we used pre-screening prioritization tools to identify priority studies for manual screening (Section A.3).

The search update returned 8,168 unique references. After searching titles and abstracts for an exhaustive list of country and city terms to limit results to those pertaining to the United States (U.S.), 3,067 references containing only foreign country or city terms were removed, leaving a total of 5,101 potentially relevant studies (5,196 when including seed studies). Of these, 480 references contained U.S. terms, and 4,621 references lacking any country or city terms comprised a set of “unclear” studies.

Next, we used modeling tools to prioritize references within the 5,101 potentially relevant search results for screening. First, we assessed references for their similarity to a set of seeds related to the health or climate change effects of IRC that topic subject matter experts identified from within the 2022 search results. We used a validated ICF modeling tool to analyze search results retrieved by the bibliographic platform searches (see Section A.1.3.1) and rank studies based on their similarity to the seeds on a scale of 0 to 6, with 6 indicating the highest potential relevance.

We then used a Large Language Model (LLM) Claude v3.5 Sonnet 2 to assess predictions of the ICF modeling tool by evaluating titles and abstracts of the 639 studies ranked with a score of 5 or 6 for applicability to topic areas 4 and 5. We used prompts (see Table 4) that aligned with the manual screening guidelines in Section A.6.

In total, these automated prioritization methods identified 160 studies for manual review (see Section A.3). Specifically, the following steps were used to identify the 160 studies for manual screening. The number of studies listed for each step (n) is the number of new studies identified from that step (i.e., excluding studies previously flagged during a prior step):

- 5 or 6 score for applicability to topic areas, title/abstract indicates U.S. results, and LLM validated topic applicability for Topic 4 OR Topic 5 (+ n = 32);
- 5 or 6 score for applicability to topic areas, and LLM validated topic applicability for Topic 4 AND Topic 5 (+ n = 34);
- 5 or 6 score for applicability to topic areas, and LLM validated applicability for Topic 5 only (i.e., Topic 4 = No and Topic 5 = yes) (+ n = 17);

- 5 or 6 score for applicability to topic areas, and GenAI validated applicability for Topic 4 only (i.e., Topic 4 = Yes and Topic 5 = No), and has PubMed Central ID (+ n = 42);
- 5 or 6 score for applicability to topic areas, and LLM validated applicability for Topic 4 only (i.e., Topic 4 = Yes and Topic 5 = No), and found via PubMed Search (+ n = 27);
- 5 or 6 score for applicability to topic areas, and LLM validated applicability for Topic 4 only (i.e., Topic 4 = Yes and Topic 5 = No), and found via EBSCO Search (+ n = 4);
- Studies in the "Recent Seeds" folder that were not already flagged (+ n = 4):
    - Note that we explicitly removed seed studies in the earlier prioritization to eliminate seeds included in the original report. However, this step ensured that we considered all recent seeds published in late 2022–January 2025.

Table 4. LLM Prompts Used to Assess Search Results

Relevance to Topic Area 4	Relevance to Topic Area 5 (including Health)
Objective	
Identify articles that examine the human health effects or impacts of exposure to indoor air pollution from residential indoor combustion sources, using the merged text of title and abstract. Highlight review or synthesis articles	Identify articles that examine outdoor air quality/air pollution and greenhouse gas impacts from residential indoor combustion sources, using the merged text of the title and abstract. Highlight articles that estimate health impacts of outdoor air pollution from indoor residential combustion sources.
Inclusion Criteria	
Include articles that: 1. Assess human health effects from exposure to indoor air pollutants linked to residential indoor combustion, including $PM_{2.5}$, VOCs, CO, SO_2, and NO_x. 2. Examine human intake or dose in relation to built environment factors such as building age, type, and size; ventilation systems such as range hoods and bathroom fans; filtration systems such as standalone air purifiers and minimum efficiency reporting value (MERV)-rated heating, ventilation and air conditioning (HVAC) filters; measures to improve system performance such as air duct cleaning, Human behavior such as cooking habits and time spent near the pollution source.	Include articles that: 1. Quantify the impact of indoor residential combustion (either at the individual household or aggregate level) to outdoor air quality and climate change impacts in or near the US. 2. Quantify or link the impact of indoor combustion-related pollution that affects outdoor air quality/climate change with an associated health impact in the US. 3. Provide list and magnitude of pollutants from indoor residential combustion associated with climate or outdoor air quality (source apportionment) study.
Exclusion Criteria	

Relevance to Topic Area 4	Relevance to Topic Area 5 (including Health)
Exclude articles that are not broadly applicable to U.S. populations, including studies on fuel sources uncommon in the U.S. (e.g., dung burning), health outcomes not prevalent in the U.S. (e.g., tuberculosis), healthcare settings in lower- and middle-income countries that differ significantly from the U.S., epidemiological studies conducted in regions with significantly higher indoor or outdoor air pollution than the U.S. (e.g., Africa, India, China). Exclude articles that focus on combustion sources unrelated to the scope, such as tobacco smoking, incense and candle burning, fireplaces and other recreational combustion activities. Exclude articles that do not focus on combustion sources in residences, homes, and households. However, note the articles that focus on these indoor combustion sources in schools.	Exclude articles that: 1. Only describe outdoor sources' (vehicle emissions, industrial sites, etc.) impact on indoor air quality. 2. Articles that do not include a value (proportion, concentration, warming potential, light absorption characteristics, etc.) related to outdoor air quality from indoor, residential combustion sources. 3. Articles that report results not broadly applicable to US populations, such as sources not used in the US (e.g., dung burning), outcomes not prevalent in the US (e.g., tuberculosis (TB)), health care settings that are too dissimilar to the US (e.g. LMIC), epidemiological evidence obtained in geographical locations where outdoor and/or indoor air pollution is much higher than the US (e.g. African countries, India, China). Exclude articles that focus on combustion sources unrelated to the scope, such as tobacco smoking, incense and candle burning, fireplaces and other recreational combustion activities. Exclude articles that do not focus on combustion sources in residences, homes, and households. However, note, the articles that focus on these indoor combustion sources in schools.
Output Format	
Each line of the input represents an article. Analyze and report on each article. For each article, return three following tab-separated fields: (1) a field containing the Article_ID; (2) a field containing the YES or NO judgement; and (3) a brief justification for the judgement.	

We note that the ability of models used at this stage to discriminate between relevant and not relevant articles was not evaluated because the compilation of additional set-aside testing data has been de-prioritized in lieu of the manual screening initiation. However, we also note that a positive model prediction indicates a relevance *potential*. Approximately 60% of prioritized positive predictions using models of this type have been judged relevant per human-based assessment (see Section A.3). This highlights the importance of manual review.

Appendix B contains the collection or article references that were prioritized by one or more models, along with the relevance score for each topic area and overall.

A.3. Manual Review

This section covers the manual screening process involved a review of article reference meta-data (e.g., title, abstract) by subject matter experts to identify articles that warrant full-text review and the process used for the full-text review. To ensure quality of manual review and consistency across screeners, subject matter experts developed and followed inclusion/exclusion criteria for both major topics. The final screening guidelines for each original topics are in Section A.6.

A.3.1. Title and Abstract Screening

We used Excel to organize the manual screening process. Two subject matter experts screened 80 article references, each, for a total of 160[4] (prioritized as described in Section A.2) and populated a custom-designed spreadsheet to document the screening decisions. Out of the 160 manually screened studies, ICF identified:

- 2 articles as relevant to impacts on outdoor air quality and climate change (research area #3) only,
- 32 articles as relevant for health impacts (research area #4) only, and
- 6 articles as relevant for both.

These 40 studies were selected for full-text review.

ICF identified an additional 58 studies as *potentially relevant* (2 for research area #3 only, 51 for research area #4 only, and 5 for both), but because these studies did not have clear IRC and/or U.S. relevance, these studies were not selected for full-text review or inclusion in this report addendum.

In addition to screening 160 studies, ICF screened reference lists from the bibliographies of articles selected for full-text review and reviewed studies identified via ad-hoc searches to support narrative development. From these ad-hoc searches, ICF identified 5 additional studies for research area #3 and 11 additional studies for research area #4, which are incorporated into the addendum as appropriate.

A.3.2. Full Text Review and Information Extraction

We obtained full text for all 40 studies identified for full-text review, plus the 16 additional studies identified via ad-hoc searches. During full-text review, subject matter experts added notes and basic study metrics to an Excel workbook. Subject matter experts also drafted an annotated bibliography for each study summarizing key findings and any noteworthy limitations.

Following full-text review and hoc searches, ICF determined that 15 studies were relevant for impacts on outdoor air quality and climate change (research area #3), 26 studies were relevant for human health impacts of IRC (research area #4), and 1 study (Michanowicz et al., 2022) was relevant to both research areas. The list below provides additional details about how these studies were identified (see tab “C-Citation Sources” in the Appendix B workbook for additional details):

- Research area #3:
  - 7 studies were identified via the 2025 systematic literature search;
  - 5 studies were found via ad-hoc searches;

[4] In most cases, the screeners reviewed titles and abstracts of the articles. Whenever articles meta-data were incomplete (e.g., lacked the full abstract text), the screeners accessed URLs included in the bibliographic metadata (if available).

  - 2 studies were identified pre-search as seed studies;
  - 1 study was an updated version of a source used in the 2022 report.
- Research area #4:
  - 12 studies were identified via the 2025 systematic literature search;
  - 11 studies were found via ad-hoc searches;
  - 2 studies were also cited in the 2022 report (retained for appropriate context);
  - 1 study was identified pre-search as a seed study.

The one study relevant to both research areas (Michanowicz et al., 2022) was found via the 2025 systematic literature search.

A.4. Other Resources Consulted

In addition to the literature obtained via searches, ICF also consulted the NEI for 2020 (United States Environmental Protection Agency, 2020), which is EPA's most recent, comprehensive, and detailed estimate of air pollutant emissions in the U.S. It is the best data source for emissions by sector of the economy and geography across the United States. It includes emissions of criteria air pollutants and precursor pollutants, along with a variety of hazardous air pollutants. Residential combustion sources are tracked in four fuel categories: Natural Gas, Oil, Wood, and Other. This database is used to inform research area #3. The NEI is released every three years based primarily upon data provided by State, Local, and Tribal air agencies for sources in their jurisdictions and supplemented by data developed by the EPA. The 2020 NEI was released in March 2023. The NEI does not include GHG emissions.

A.5. Search Strings

Table 2 defines the queries that were included in our peer-reviewed database literature searches. Each query included specific "search sets" of terms used with Boolean search command operators (AND / OR / NOT) to optimize search results relating to the research topic areas around which our search was conducted. Because this was a search update, we used the same queries from the 2022 search, although some terms were removed or added on the recommendation of subject matter experts after client consultation. Terms were searched for in the Titles and Abstracts, and PubMed queries also included select MeSH keyword search terms associated with MEDLINE's controlled vocabulary index. Because EBSCO databases do not include MeSH terms, where appropriate, equivalent terms were used in EBSCO search sets. EBSCO includes numerous databases from various research disciplines, so to help focus results, EBSCO searches typically included fewer terms than PubMed searches. Additionally, Boolean operators between terms within sets differed slightly from those used in equivalent PubMed searches. Hence, the combination of terms within each search set varied somewhat for each database platform.

All queries run in PubMed and EBSCO used filters to restrict results to English-language materials published from 2021 to 2025. EBSCO queries were additionally limited to academic publication and document types and excluded the MEDLINE database, which is included in the PubMed platform.

Table 5 lists the search sets and the terms and Boolean operators comprising the search syntax used for each set in PubMed and EBSCO queries. Google Scholar searches were modeled on the EBSCO searches. Quotation marks surrounding words required the databases to return results that exactly matched the words and word order. Asterisk (*) truncation wildcard symbols used at the end of words directed the databases to search for various word endings (e.g., "evaporat*" will search for "evaporate," "evaporates," "evaporation," and "evaporating" without requiring each word to be searched separately). PubMed searches included syntax that restricted terms to Titles and Abstracts [TIAB] or to keywords [MeSH]. EBSCO searches do not employ similar field tags.

Table 5. Search Syntax: Sets and Terms and Boolean Operators

Search Set	PubMed Search Syntax	EBSCO Search Syntax
Action	(reduce*[TIAB] OR reduction*[TIAB] OR "reducing"[TIAB] OR improve*[TIAB] OR "mitigate"[TIAB] OR mitigation*[TIAB] OR "transition"[TIAB] OR intervention*[TIAB] OR decreas*[TIAB])	(reduce* OR reduction* OR "reducing" OR improve* OR "mitigate" OR mitigation* OR "transition" OR intervention* OR decreas*)
Air Quality – General	(("Air Pollution, Indoor"[Mesh] OR "air pollution"[Mesh]) OR ((indoor*[TIAB] OR outdoor*[TIAB] OR "ambient"[TIAB]) AND ("air quality"[TIAB] OR "black carbon"[TIAB] OR "carbon dioxide"[TIAB] OR "carbon dioxides"[TIAB] OR "carbon monoxide"[TIAB] OR "carbon monoxides"[TIAB] OR "CH4"[TIAB] OR "CO2"[TIAB] OR "damp"[TIAB] OR "dampness"[TIAB] OR "dust"[TIAB] OR Emission*[TIAB] OR "formaldehyde"[TIAB] OR "fugitive"[TIAB] OR "pipe leak"[TIAB] OR "pipe leaks"[TIAB] OR evaporat*[TIAB] OR "fugitive"[TIAB] OR "methane"[TIAB] OR "mold"[TIAB] OR "mould"[TIAB] OR "nitrogen oxide"[TIAB] OR "nitrogen oxides"[TIAB] OR "nitric oxide"[TIAB] OR "nitric oxides"[TIAB] OR "nitrogen dioxide"[TIAB] OR "nitrogen dioxides"[TIAB] OR "NOx"[TIAB] OR "NO2"[TIAB] OR "ozone"[TIAB] OR "O3"[TIAB] OR "PAH"[TIAB] OR "PAHs"[TIAB] OR "Particulate Matter"[Mesh] OR "particulate matter"[TIAB] OR "fine PM"[TIAB] OR "PM 2.5"[TIAB] OR "PM2.5"[TIAB] OR "PM10"[TIAB] OR "PM 10"[TIAB] OR "pollutant"[TIAB] OR "pollutants"[TIAB] OR "pollution"[TIAB] OR "polycyclic aromatic hydrocarbons"[TIAB] OR "SO2"[TIAB] OR "sulfur dioxide"[TIAB] OR "sulfur dioxides"[TIAB] OR "ultrafine particle"[TIAB] OR "ultrafine particles"[TIAB] OR "VOCs"[TIAB] OR "VOC"[TIAB] OR "TVOC"[TIAB] OR "TVOCs"[TIAB] OR "volatile	((indoor* OR outdoor* OR "ambient") AND ("air quality" OR "black carbon" OR "carbon dioxide" OR "carbon dioxides" OR "carbon monoxide" OR "carbon monoxides" OR "CH4" OR "CO2" OR "damp" OR "dampness" OR "dust" OR Emission* OR "formaldehyde" OR "fugitive" OR "pipe leak" OR "pipe leaks" OR evaporat* OR "fugitive" OR "methane" OR "mold" OR "mould" OR "nitrogen oxide" OR "nitrogen oxides" OR "nitric oxide" OR "nitric oxides" OR "nitrogen dioxide" OR "nitrogen dioxides" OR "NOx" OR "NO2" OR "ozone" OR "O3" OR "PAH" OR "PAHs" OR "Particulate Matter"[Mesh] OR "particulate matter" OR "fine PM" OR "PM 2.5" OR "PM2.5" OR "PM10" OR "PM 10" OR "pollutant" OR "pollutants" OR "pollution" OR "polycyclic aromatic hydrocarbons" OR "SO2" OR "sulfur dioxide" OR "sulfur dioxides" OR "ultrafine particle" OR "ultrafine particles" OR "VOCs" OR "VOC" OR "TVOC" OR "TVOCs" OR "volatile organic compound" OR "volatile organic compounds"))

Search Set	PubMed Search Syntax	EBSCO Search Syntax
	organic compound"[TIAB] OR "volatile organic compounds"[TIAB])))	
Appliances	(("Air Conditioning"[Mesh] OR "air conditioning"[TIAB] OR "candle"[TIAB] OR "candles"[TIAB] OR "generator"[TIAB] OR "generators"[TIAB] OR "kerosene lamp"[TIAB] OR "kerosene lamps"[TIAB] OR "kerosene wick lamp"[TIAB] OR "kerosene wick lamps"[TIAB] OR "open wick kerosene lamp"[TIAB] OR "open wick kerosene lamps"[TIAB] OR "oil lamp"[TIAB] OR "oil lamps"[TIAB] OR "lamp oil"[TIAB] OR "hurricane lamp"[TIAB] OR "hurricane lamps"[TIAB] OR "kerosene lantern"[TIAB] OR "kerosene lanterns"[TIAB] OR "grill"[TIAB] OR "grills"[TIAB] OR "grilling"[TIAB] OR "stove"[TIAB] OR "stoves"[TIAB] OR "cook"[TIAB] OR "cooking"[TIAB] OR "boiler"[TIAB] OR "boilers"[TIAB] OR "furnace"[TIAB] OR "furnaces"[TIAB] OR "clothes dryer"[TIAB] OR "clothes dryers"[TIAB] OR "cooking burner"[TIAB] OR "cooking burners"[TIAB] OR "oil burner"[TIAB] OR "oil burners"[TIAB] OR "heater"[TIAB] OR "heaters"[TIAB] OR "appliance"[TIAB] OR "appliances"[TIAB] OR "oven"[TIAB] OR "ovens"[TIAB] OR "heating"[TIAB] OR fireplace*[TIAB] OR "fire place"[TIAB] OR "fire places"[TIAB] OR "cookstove"[TIAB] OR "cookstoves"[TIAB] OR "gas range"[TIAB] OR "gas ranges"[TIAB] OR "electric ranges"[TIAB] OR "electric range"[TIAB] OR "LPG range"[TIAB] OR "LPG ranges"[TIAB] OR "CNG range"[TIAB] OR "CNG ranges"[TIAB] OR "propane range"[TIAB] OR "propane ranges"[TIAB] OR "convection range"[TIAB] OR "convection ranges"[TIAB] OR "induction range"[TIAB] OR "induction ranges"[TIAB] OR "methane range"[TIAB] OR "methane ranges"[TIAB] OR "heating, ventilation, and air conditioning"[TIAB] OR "HVAC"[TIAB] OR "woodstove"[TIAB] OR "woodstoves"[TIAB] OR “heat pump”[TIAB] OR “heat pumps”[TIAB]) NOT ("ranged"[TIAB] OR "diet"[TIAB] OR "dietary"[TIAB]))	(“Appliance” OR “appliances” OR “stoves” OR “fireplaces” OR “heaters” OR “air conditioners” OR “cookstoves” OR “furnaces” OR “heat pump” OR “heat pumps” OR ((“range” OR “ranges”) AND (“gas” OR “electric” OR “LPG” OR “CNG” OR “propane” OR “convection” OR “induction” OR "natural gas" OR “methane”)))
Exposure Reduction	("air vent"[TIAB] OR "air vents"[TIAB] OR "air venting"[TIAB] OR "air cleaning"[TIAB] OR "air cleaner"[TIAB] OR "air cleaners"[TIAB] OR "air control"[TIAB] OR "air controls"[TIAB] OR "air filter"[TIAB] OR "air filters"[TIAB] OR "air filtration"[TIAB] OR "air purifier"[TIAB] OR "air purifiers"[TIAB] OR "air purification"[TIAB] OR "bathroom fan"[TIAB] OR "bathroom fans"[TIAB] OR "bathroom exhaust fan"[TIAB]	("duct cleaning" OR "energy efficiency" OR "exposure reduction" OR "filter replacement" OR "moisture control" OR "range hood" OR "range hoods" OR “ventilation” OR “energy efficient” OR “energy-efficient” OR “energy saving” OR “energy-saving” OR “energy star” OR “energy-star” OR “demand management” OR “demand-

Search Set	PubMed Search Syntax	EBSCO Search Syntax
	OR "bathroom exhaust fans"[TIAB] OR "duct cleaning"[TIAB] OR "energy efficiency"[TIAB] OR "exposure reduction"[TIAB] OR "filter replacement"[TIAB] OR "moisture control"[TIAB] OR "air quality control"[TIAB] OR "air pollution control"[TIAB] OR "range hood"[TIAB] OR "range hoods"[TIAB] OR "ventilation"[TIAB] OR "unvented"[TIAB] OR "weatherization"[TIAB] OR "energy efficient"[TIAB] OR "energy-efficient"[TIAB] OR "energy saving"[TIAB] OR "energy-saving"[TIAB] OR "energy star"[TIAB] OR "energy-star"[TIAB] OR "decarbonization"[TIAB] OR "air capture"[TIAB] OR "building performance standard"[TIAB] OR "building performance standards"[TIAB] OR "net zero"[TIAB] OR "zero energy"[TIAB] OR "electrification"[TIAB] OR "zero emission"[tiab] OR "zero-emission"[tiab] OR "zero-energy"[tiab])	management" OR "decarbonization" OR "air capture" OR "building performance standard" OR "building performance standards" OR "net zero" OR "zero energy" OR "electrification" OR "zero emission" OR "zero-emission" OR "zero-energy" OR ("Bathroom" AND ("fan" OR "fans" OR "exhaust")) OR ("air" AND ("vent" OR "vents" OR "venting" OR "cleaning" OR "cleaner" OR "cleaners" OR "control" OR "controls" OR "filter" OR "filters" OR "filtration" OR "purifier" OR "purifiers" OR "purification" OR "quality control" OR "pollution control")))
Health	(disease*[TIAB] OR "Health"[TIAB] OR illness*[TIAB] OR "Morbidity"[TIAB] OR "Morbidity"[Mesh] OR "Disability Adjusted Life Year"[TIAB] OR "Disability Adjusted Life Years"[TIAB] OR "asthma"[TIAB] OR wheez*[TIAB] OR "respiratory"[TIAB] OR "breathlessness"[TIAB] OR "breathing"[TIAB] OR "acute lower respiratory infection"[tiab] OR "acute lower respiratory infections"[tiab] OR "adverse birth outcome"[tiab] OR "adverse birth outcomes"[tiab] OR "adverse pregnancy outcome"[tiab] OR "adverse pregnancy outcomes"[tiab] OR "ALRI"[tiab] OR "birth defect"[tiab] OR "birth defects"[tiab] OR "birth weight"[tiab] OR "bronchitis"[tiab] OR "cardiovascular disease"[tiab] OR "cardiovascular diseases"[tiab] OR "cerebrovascular disease"[tiab] OR "cerebrovascular diseases"[tiab] OR "chronic obstructive pulmonary disease"[tiab] OR "COPD"[tiab] OR "CVD"[tiab] OR "diabetes"[tiab] OR "eclampsia"[tiab] OR "emphysema"[tiab] OR "high blood pressure"[tiab] OR "hypertension"[tiab] OR "ischemic heart disease"[tiab] OR "ischemic heart diseases"[tiab] OR "lung cancer"[tiab] OR "pre-eclampsia"[tiab] OR "preeclamsia"[tiab] OR "preterm birth"[tiab] OR "pre-term birth"[tiab] OR "stroke"[tiab] OR "developmental"[tiab] OR "reproductive"[tiab])	(disease* OR "Health" OR illness* OR "Morbidity" OR "Disability Adjusted Life Year" OR "Disability Adjusted Life Years" OR "asthma" OR wheez* OR "respiratory" OR "breathlessness" OR "breathing" OR "acute lower respiratory infection" OR "acute lower respiratory infections" OR "adverse birth outcome" OR "adverse birth outcomes" OR "adverse pregnancy outcome" OR "adverse pregnancy outcomes" OR "ALRI" OR "birth defect" OR "birth defects" OR "birth weight" OR "bronchitis" OR "cardiovascular disease" OR "cardiovascular diseases" OR "cerebrovascular disease" OR "cerebrovascular diseases" OR "chronic obstructive pulmonary disease" OR "COPD" OR "CVD" OR "diabetes" OR "eclampsia" OR "emphysema" OR "high blood pressure" OR "hypertension" OR "ischemic heart disease" OR "ischemic heart diseases" OR "lung cancer" OR "pre-eclampsia" OR "preeclamsia" OR "preterm birth" OR "pre-term birth" OR "stroke" OR "developmental" OR "reproductive")
Indoor Air Quality	("Air Pollution, Indoor"[Mesh] OR (indoor*[TIAB] AND ("air quality"[TIAB] OR "black carbon"[TIAB] OR "carbon	(indoor* AND ("air quality" OR "black carbon" OR "carbon dioxide" OR "carbon dioxides" OR "carbon monoxide" OR

Search Set	PubMed Search Syntax	EBSCO Search Syntax
	dioxide"[TIAB] OR "carbon dioxides"[TIAB] OR "carbon monoxide"[TIAB] OR "carbon monoxides"[TIAB] OR "CH4"[TIAB] OR "CO2"[TIAB] OR "damp"[TIAB] OR "dampness"[TIAB] OR "dust"[TIAB] OR Emission*[TIAB] OR "formaldehyde"[TIAB] OR "fugitive"[TIAB] OR "pipe leak"[TIAB] OR "pipe leaks"[TIAB] OR evaporat*[TIAB] OR "fugitive"[TIAB] OR "methane"[TIAB] OR "mold"[TIAB] OR "mould"[TIAB] OR "nitrogen oxide"[TIAB] OR "nitrogen oxides"[TIAB] OR "nitric oxide"[TIAB] OR "nitric oxides"[TIAB] OR "nitrogen dioxide"[TIAB] OR "nitrogen dioxides"[TIAB] OR "NOx"[TIAB] OR "NO2"[TIAB] OR "ozone"[TIAB] OR "O3"[TIAB] OR "PAH"[TIAB] OR "PAHs"[TIAB] OR "Particulate Matter"[Mesh] OR "particulate matter"[TIAB] OR "fine PM"[TIAB] OR "PM 2.5"[TIAB] OR "PM2.5"[TIAB] OR "PM10"[TIAB] OR "PM 10"[TIAB] OR "pollutant"[TIAB] OR "pollutants"[TIAB] OR "pollution"[TIAB] OR "polycyclic aromatic hydrocarbons"[TIAB] OR "SO2"[TIAB] OR "sulfur dioxide"[TIAB] OR "sulfur dioxides"[TIAB] OR "ultrafine particle"[TIAB] OR "ultrafine particles"[TIAB] OR "VOCs"[TIAB] OR "VOC"[TIAB] OR "TVOC"[TIAB] OR "TVOCs"[TIAB] OR "volatile organic compound"[TIAB] OR "volatile organic compounds"[TIAB])))	"carbon monoxides" OR "damp" OR "dampness" OR "dust" OR Emission* OR "Formaldehyde" OR "fugitive" OR "pipe leak" OR "pipe leaks" OR evaporat* OR "methane" OR "mold" OR "mould" OR "nitrogen oxide" OR "nitrogen oxides" OR "nitric oxide" OR "nitric oxides" OR "nitrogen dioxide" OR "nitrogen dioxides" OR "NOx" OR "NO2" OR "ozone" OR "PAH" OR "PAHs" OR "particulate matter" OR "fine PM" OR "PM 2.5" OR "PM2.5" OR "PM10" OR "PM 10" OR "pollutant" OR "pollutants" OR "pollution" OR "polycyclic aromatic hydrocarbons" OR "sulfur dioxide" OR "sulfur dioxides" OR "ultrafine particle" OR "ultrafine particles" OR "volatile organic compound" OR "volatile organic compounds"))
Outdoor Air Quality	("outdoor air"[TIAB] OR "climate change"[TIAB] OR "Climate Change"[Mesh] OR "air pollution"[Mesh] OR "greenhouse gas"[TIAB] OR "greenhouse gases"[TIAB] OR ((outdoor*[TIAB] OR "ambient"[TIAB]) AND "pollution"[TIAB] OR pollutant*[TIAB] OR "climate"[TIAB] OR "warming"[TIAB] OR "temperature"[TIAB] OR "air quality"[TIAB]))	("outdoor air" OR "climate change" OR "greenhouse gas" OR "greenhouse gases" OR ((outdoor* OR "ambient") AND "pollution" OR pollutant* OR "climate" OR "warming" OR "temperature" OR "air quality"))
Review Study	(review*[TIAB] OR "review"[Publication Type] OR "synthesis"[TIAB] OR "meta-analysis"[TIAB] OR "meta-analyses"[TIAB] OR "Meta-analysis"[Publication Type] OR "meta-analysis as Topic"[Mesh] OR "weight of evidence"[TIAB] OR "weights of evidence"[TIAB] OR "systematic"[TIAB] OR assess*[TIAB])	(review* OR "meta-analysis")
Source	(("biomass"[TIAB] OR "Combustion"[TIAB] OR "Cooking"[TIAB] OR "fuel"[TIAB] OR "fossil fuels"[Mesh] OR "Fuel Oils"[Mesh] OR "ethanol"[TIAB] OR "alcohol"[TIAB] OR "pellet"[TIAB] OR "pellets"[TIAB] OR "natural gas"[TIAB] OR "gas"[TIAB] OR "gasoline"[TIAB] OR "LNG"[TIAB] OR "CNG"[TIAB] OR "LPG"[TIAB] OR "methane"[TIAB] OR	("combustion" AND ("biomass" OR "fuel" OR "natural gas" OR "wood" OR "kerosene" OR "methane" OR "propane" OR "oil" OR "firewood" OR "pellets" OR ("burning" AND ("refuse" OR "trash"))))

Search Set	PubMed Search Syntax	EBSCO Search Syntax
	"propane"[TIAB] OR "trash burning"[TIAB] OR "refuse burning"[TIAB] OR "distillate oil"[TIAB] OR "petroleum"[TIAB] OR "kerosene"[TIAB] OR "wood"[TIAB] OR "firewood"[TIAB] OR "coal"[TIAB] OR "charcoal"[TIAB]) NOT ("alcohol use"[TIAB] OR "alcohol drinking"[TIAB] OR "alcohol abuse"[TIAB] OR "alcohol ingestion"[TIAB] OR "alcohol consumption"[TIAB] OR "blood gas"[TIAB] OR "gas station"[TIAB] OR "gas chromatography"[TIAB]))	
Source Qualifier	("source apportionment"[TIAB] OR "source attribution"[TIAB] OR "source"[TIAB] OR "sources"[TIAB] OR concentration*[TIAB] OR contribution*[TIAB] OR "contributing"[TIAB] OR "level"[TIAB] OR "levels"[TIAB])	("source apportionment" OR "source attribution" OR "source" OR "sources" OR concentration* OR contribution* OR "contributing" OR "level" OR "levels")
Type	("Home"[TIAB] OR "Homes"[TIAB] OR "House"[TIAB] OR "Houses"[TIAB] OR "Housing"[TIAB] OR household*[TIAB] OR Indoor*[TIAB] OR "Residential"[TIAB] OR "residence"[TIAB] OR "residences"[TIAB])	("Home" OR "Homes" OR "House" OR "Houses" OR "Housing" OR household* OR Indoor* OR "Residential" OR "residence" OR "residences")

A.6. Manual Screening Guidelines

Screeners reviewing references for relevance followed detailed screening instructions developed by the subject matter experts. The screening instructions clearly defined each research topic area and the specific inclusion and exclusion criteria to be applied when making determinations. For any references without abstracts or with truncated abstracts, screeners were instructed to follow URLs included with the bibliographic information where available. Screeners recorded in a comments field the relevant topic areas, notes about relevancy, and whether articles had a focus that did not include the United States.

Exclusion criteria included the following:

- Not written in English,
- Published before 2021,
- Pertains to catastrophic incidents (e.g., house fires),
- Pertains to smoking/tobacco use (including second-hand exposure),
- Pertains to candles, incense, or outdoor sources affecting indoor air quality (e.g., vehicles),
- Is not applicable to residential combustion in the United States.

References not matching the exclusion criteria were included if they pertained to chemicals released indoors from use of IRC appliances that burn fuel. Appliances were defined as fireplaces or those used for cooking, home heating, water heating, and laundry. Residences were defined as people's homes. Fuels were defined as those reasonably expected to be used in the United States, including liquid or solid petroleum products (e.g., gas, oil, propane, kerosene). References about coal or animal dung not used inside residences in the U.S. were marked as not relevant.

Because each topic area focused on unique research questions, a clear definition of what should be marked as relevant for each topic was provided to screeners along with specific examples. Below are the topic-specific definitions about inclusion and exclusion provided to screeners.

A.6.1. Topic 4. Health Impacts from Residential Exposure to Pollutants from Indoor Combustion Sources (Research Area #4)

Adverse human health effects, indoors, from occupants' exposure to pollutants emitted from IRC in U.S. homes:

- Would not include general exposure risks to pollutants unless there is an explicit link to IRC.
- May apply to individual air pollutants measured indoors or mixtures of air pollutants, so long as directly result from IRC.
- Human health effects could include, among others, asthma incidence, asthma or allergy exacerbation, respiratory symptoms, cardiovascular symptoms, promotion of infectious disease (e.g., pneumonia, acute LRIs), cancer, neurodevelopmental effects, premature mortality (all-cause and cause-specific), and morbidity.
- Tuberculosis, malaria, and other health outcomes not prevalent in the United States are not of interest.
- Included studies may present health thresholds for indoor exposure to combustion-related pollutants, including U.S.-based and non-U.S. based, such as WHO or Canadian indoor air quality guidelines.

A.6.2. Topic 5. Contributions to Outdoor Air Quality and Climate Change (Research Area #3)

Contribution of the appliance's indoor emissions to outdoor air pollution (e.g., criteria air pollutants, air toxics, and GHGs):

- Includes effects on climate from indoor combustion.
- "Air toxics" are toxic contaminants. There is a long list. PAH or particulate organic matter (POM) are the most likely to be mentioned, along with VOCs, ultrafine particles, formaldehyde, and acetaldehyde. Additional resources on air pollutants found can be consulted.
- "Criteria pollutants" are:
    - $PM_{2.5}$
    - CO

  - SO_2
  - NO_x
- "GHGs" include:
  - CO_2
  - CH_4 – particularly important, including from natural gas leaks
  - Nitrous oxide (N_2O)
- "Contribution" can mean amount of emissions (tons/year), or concentration (ppm; ug/m3), and/or impacts on climate change, such as changes in temperature, changes in optical thickness/radiative balance, etc. It can also relate to formation of secondary pollutants in the ambient air (e.g., NOx emissions related to ozone formation, VOC emissions related to secondary organic aerosols).

A.6.3. Topic 6. Exposures and Health Impacts from Ambient Exposure and Climate Change

Combination of Topics 4 and 5 (i.e., research areas #3 and #4). Adverse human health effects from ambient (e.g., outdoor) exposure to pollutant mixtures (i.e., not individual pollutants that can also be combustion by-products) emitted from the appliances and subsequently from the indoor residential air to the outdoors and attributable to appliances used in U.S. homes:

- Can include health impacts of climate change if they are linked to indoor combustion sources.
- Similar to Topic 4 (i.e., health impacts from IRC). The focus is on health impacts, except here the exposures occur outdoors and can also consider the health impacts of climate change resulting from these emissions.
  - The effects on climate from indoor combustion are under Topic 5.
- Can include modeling studies that are relevant to Topic 5 (i.e., contributions to outdoor air quality and climate change) but additionally make a health impact calculation.

Appendix B. Full Collection of Identified Peer Reviewed and Gray Literature Articles

This appendix is delivered as a workbook named:

ICF_IRC_Addendum_Appendix_B_All References.xlsx.

The workbook contains a complete list of references subject to prioritization (n = 5,196), with flags for the 160 studies screened by title and abstract (i.e., manual screening) and the 40 studies selected for full-text review. Note that not all articles referenced in this workbook were reviewed to develop the report narrative. The entire collection of potentially relevant articles is provided for completeness and to facilitate future research.

The workbook also contains a list of sources cited in the addendum, along with notes about the topic covered and how the source was identified.

About ICF

ICF (NASDAQ:ICFI) is a global consulting and digital services company with over 7,000 full- and part-time employees, but we are not your typical consultants. At ICF, business analysts and policy specialists work together with digital strategists, data scientists and creatives. We combine unmatched industry expertise with cutting-edge engagement capabilities to help organizations solve their most complex challenges. Since 1969, public and private sector clients have worked with ICF to navigate change and shape the future. Learn more at icf.com.