


Literature Review on the Impacts of Residential Combustion

Final Report

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American Lung Association

ICF

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Acronyms and Abbreviations

Term	Definition
AHS	American Housing Survey
BAAQMD	(San Francisco) Bay Area Air Quality Management District
BaP	benzo [alpha] pyrene
BTU	British thermal unit
CAP	criteria air pollutant
CH_4	methane
CNG	compressed natural gas
CO	carbon monoxide
CO_2	carbon dioxide
CO_2e	carbon dioxide equivalent
COPD	chronic obstructive pulmonary disease
EC	elemental carbon
EPA	U.S. Environmental Protection Agency
GBD	Global Burden of Disease
GHG	greenhouse gas(es)
GJ, MJ	gigajoule, megajoule, a measure of energy output
HAP	hazardous air pollutants (also known as toxic air contaminants (TAC) or air toxics)
HONO	nitrous acid (also represented as HNO_2)
IAQ	indoor air quality
IRC	indoor residential combustion
LMIC	low and middle income country(ies)
LPG	liquified petroleum gas
LRI	lower-respiratory infection
M_{LAC}	mass of light absorbing carbon (i.e., black carbon) particulate
MMT	million metric tons (a metric ton is 1,000 kg)
NHANES	National Health and Nutrition Examination Survey
NEI	National Emissions Inventory
NLP	natural language processing (method to prioritize and predict potential relevance of studies to one or more research areas)
NH_3	ammonia
NMHC	nonmethane hydrocarbon
NO	nitric oxide
NO_2	nitrogen dioxide
NO_x	nitrogen oxides (including nitric oxide and nitrogen dioxide)
OC	organic carbon
PAH	polycyclic aromatic hydrocarbon
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)
PMF	positive matrix factorization

PN, PNC	particle number, particle number concentration (measure particulate by count rather than mass)
ppm, ppb	parts per million, parts per billion
RECS	Residential Energy Consumption Survey
RNG	renewable natural gas
RWC	residential wood combustion
SOA	secondary organic aerosol
SCAQMD	South Coast Air Quality Management District
SO_2	sulfur dioxide
TAC	toxic air contaminants
TSP	total suspended particulate
UFP	ultrafine particulate
VOC	volatile organic compound

Executive Summary

Efforts have increased recently to understand the impacts of combustion occurring within the home and to mitigate its effects on indoor air quality (IAQ) and human health. Mitigation to eliminate some sources of indoor residential combustion (IRC) emissions can include upgrades to combustion appliances, to installation of ventilation or filtration devices and guidance on their most effective use, and residential building electrification. To our knowledge, no comprehensive review of scientific literature addresses the various sources and impacts of IRC in the United States. This report aims to fill that gap by documenting the state of research on IRC in the United States, specifically on residential combustion appliances and their relation to four research areas:

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

(2) Emission profiles from IRC appliances and their impacts on 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.

We focus on 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). In most cases, we also do not evaluate residential combustion that typically occurs outside the home, such as barbecuing and pool heating.

Sources of IRC and prevalence in U.S. homes

Although nearly all 118 million U.S. housing units use electricity, approximately two-thirds also rely on IRC for space or water heating, clothes drying, cooking, decoration (fireplaces), and other uses. Of the U.S. households relying on IRC for the uses considered here, more than half use natural gas, and its usage generally increases with household income and home ownership. Residential natural gas is used primarily for space and water heating (about 60 million households) and cooking (about 40 million households), with inconsistent use of kitchen range hoods to vent the cooking emissions outdoors. About 7 million gas fireplaces are in use, with potentially 2 million or more not enclosed and exposing the living space to combustion. About 1 in 7 U.S. households use other fossil fuels (e.g., propane, fuel oil, or kerosene). Propane (also known as LPG) is the most prevalent (6% of households). Six million households use propane for cooking, and 4 million use it for space or water heating, particularly in rural areas and mobile homes and particularly in the northeastern United States. Although household usage of heating oil has been declining domestically for decades, about 5 million households still use it for primary heating, mainly in the Northeast. About 1 in 10 U.S. households use wood as a secondary source of space heating, with enclosed and vented woodstoves, primarily single-family homes and mobile homes.

Appliance emissions and IAQ

Combustion appliances emit a suite of air pollutants [including hazardous air pollutants (HAPs) and criteria-based air pollutants (CAPs)] at levels that depend on appliance age, maintenance status, operator behavior, usage setting or intensity, and fuel type, among other factors. Their impacts on IAQ can depend on whether the appliance is vented, how often the appliance is on, and how the appliance is used, in addition to the type of fuel. Gas kitchen appliances can emit substantial amounts of carbon monoxide (CO) and nitrogen oxides (NOx) and modest amounts of particulate matter (PM) and polycyclic aromatic hydrocarbons (PAHs). Levels can be highly variable, while what is being cooked can substantially add to the emissions. The impact on IAQ can extend well beyond the kitchen, particularly when exhaust fans are not available or not used or when the fans are not vented outdoors. Relative to gas stoves and ovens, gas clothes dryers can emit PM at similar levels but have a smaller impact on IAQ. Although gas heaters—especially gas water heaters—tend to have substantially higher emissions, it is the kitchen appliances that tend to be unvented and directly located in the living area of the house. Appliances using propane and kerosene emit at higher rates than those using natural gas, and they might or might not exhaust to the living area. Residential wood combustion (RWC) can substantially increase indoor levels of CO, NOx, PM, PAHs, benzene, and chromium, sometimes beyond the room where combustion occurs. Such effects, however, can be mitigated by using newer and closed-door appliances. Pelletized fuels generally emit at lower levels than wood fuels, although the type of pellet is a factor, along with appliance age, maintenance status, and operator behavior. Housing size, type, and condition can be confounding factors, although this report does not investigate these topics in detail.

The United States has no residential indoor air quality standards or guidelines. The U.S. Environmental Protection Agency does not regulate indoor air, although other agencies have developed recommended thresholds specifically for indoor occupational exposures. Ambient (outdoor) guidelines might not be applicable to indoor exposures. Peak indoor concentrations of air pollutants generated by indoor sources can be higher than outdoors, while indoor concentrations of outdoor pollutants can be lower. Duration, activity, and temporal patterns of exposure, air pollutant co-exposures, and PM size and chemical composition are likely different indoors and outdoors, which could influence associated health effects.

Outdoor air quality and climate change impacts of IRC

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 HAPs, CAPs, and greenhouse gases (GHG). 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 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 black carbon 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). Nationally, natural gas also is responsible for about two-thirds of all residential combustion emissions of ammonia (NH_3) and NOx, while RWC is responsible for over 95% of all outdoor residential combustion emissions of CO, volatile organic compounds (VOC), PM, and a range of toxic compounds including PAHs. Residential use of oil and other fuels are primarily associated with emissions of sulfur dioxide (SO_2), for which these fuels comprise 55% of the residential combustion inventory.

Health impacts resulting from indoor and outdoor exposure to air pollutants generated by IRC

A large body of research is available on the detrimental health effects of exposure to air pollution from all types of sources, and evidence is strong that long-term exposure to ambient $PM_{2.5}$, ambient ozone, and household air pollution contributes to premature mortality and increased risk of illness, including ischemic heart disease, stroke, chronic obstructive pulmonary disease (COPD), lung cancer, type 2 diabetes, and lower respiratory infections (LRIs) such as pneumonia (Health Effects Institute, 2020).

In the past two decades, peer-reviewed literature on health effects of exposure to IRC has largely targeted low- and middle-income countries (LMIC). A review of literature from the systematic search we conducted revealed that fewer than 15% of primary studies focused on the United States, while over 25% were conducted in LMIC and over 40% were global studies (often with an emphasis on LMIC) or with undefined geography. Fewer than 5% of the review studies target the United States. Moreover, we found only a limited number of studies focusing on the United States that examined IRC-related health effects. Most targeted indoor air pollutants not specific to combustion sources or did not report associations between exposure to air pollutants generated by IRC and specific health effects. Regardless of geography, both primary studies and review studies often isolated the health effects of a single pollutant (e.g., $PM_{2.5}$, NO_2) instead of examining health effects associated with combustion of a specific fuel (e.g., natural gas, wood) or use of a specific type of appliance (e.g., gas stove, wood stove). Although we found several modeling studies reporting health impact estimates associated with IRC sources, none of the studies we reviewed estimated the health impact of IRC from all sources considering exposures both indoors and outdoors.

The assessed primary and review studies report that *indoor* exposure to NO_2 or gas cooking can exacerbate asthma symptoms, wheeze, LRIs, and result in reduced lung function parameters in children, particularly in the absence of ventilation and for children living with asthma or allergies; evidence for health effects in adults, however, is limited and inconsistent. *Indoor* exposure to air pollutants from RWC is associated with LRIs in children and might be associated with upper respiratory infections, wheeze, and cough. Nitrous acid (HONO) and ultrafine particulate (UFP) from

IRC could exacerbate asthma but adverse health effects from indoor exposure to these pollutants are understudied, and existing evidence is limited and inconclusive. Although formaldehyde and PAHs are emitted during IRC, and the harmful health effects from exposure to these pollutants are well known, we reviewed no studies isolating effects because of exposures originating specifically from IRC instead of many other potential sources (e.g., smoking, candle burning, building materials, and consumer products).

Sparse literature on health effects of *outdoor* exposure from IRC in the United States reports consistent associations between higher pollution levels and detrimental respiratory effects in children from exposure to RWC pollutants, including worse lung function for children with asthma, but mixed results for cough, and wheeze. Therefore, improvements to IAQ should aim for reducing emissions overall, not just transferring air pollutants from indoors to outdoors, to avoid community-level adverse health effects from outdoor exposure to pollutants originated indoors.

Consistent with research on health effects from overall exposure to air pollution, the populations most vulnerable to detrimental health effects indoors and outdoors from air pollution resulting from IRC are children, particularly indigenous children, other susceptible populations (individuals with asthma or cardiopulmonary diseases, pregnant people, older individuals), and people in low-wealth or rural communities.

Several modeling studies estimated exposure-related health impacts due to *outdoor* air pollution from *IRC sources not characterized by fuel type*. The magnitude of U.S. mortality burden attributable to outdoor exposure to $PM_{2.5}$ from IRC was estimated at fewer than 10,000 deaths annually by three studies modeling impacts in 2005 and 2015 (Fann et al., 2013; Penn et al., 2017; Thakrar et al., 2020); this burden comprises less than 0.5% of annual U.S. mortality [approximately 2,500,000 U.S. deaths in 2010., as reported by CDC (National Center for Health Statistics (U.S.), 2013)] and less than 5% of annual outdoor air pollution-attributable U.S. mortality [approximately 300,000 annual U.S. deaths, as estimated by (Lelieveld et al., 2020)]. U.S. mortality impacts related to outdoor exposure to $PM_{2.5}$ from residential buildings have shown a decreasing trend in the past decade, driven by reductions in wood and biomass combustion (Buonocore & Salimifard, 2021).

Two modeling studies examined impacts from residential natural gas and wood combustion in U.S. locations. A 2018 California modeling study by Zhu et al. (2020) showed that reductions in *outdoor* $PM_{2.5}$ concentrations achieved by replacing *natural gas appliances* with electrical appliances would result in 354 fewer annual deaths in the state [or approximately 0.1% of the total 270,000 annual deaths in California, in 2018, as reported by California Health & Human Services Agency (California Health and Human Services, 2021)]. Another modeling study conducted in the Pacific Northwest (Regional Technical Forum, 2014) estimated *outdoor* $PM_{2.5}$ health benefits from reductions in heating-related RWC in the Pacific Northwest in 2017, finding that a 100% reduction in wood smoke emissions from these sources could result in 200–500 fewer annual deaths [or approximately 0.5% of the total 108,000 annual deaths reported for Oregon, Washington, and Idaho in 2017 by CDC (Centers for Disease Control and Prevention, 2021)].

Discussion and Limitations

To the best of our knowledge, this is the first attempt to consolidate the broad literature covering four research areas that focus on IRC sources and impacts in the United States. Our findings, however, must be understood in the context of the limitations of this research effort.

First, this review, while extensive, should not be considered a comprehensive assessment of all literature on the broad range of research areas of interest. A systematic literature search was implemented for each research area in this review. We retrieved 70,865 articles from the bibliographic database searches. Additionally, we retrieved numerous technical reports and other articles from gray literature sources. 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. This effort proved challenging because articles might examine indoor air quality but not specifically the impact of pollutants from indoor combustion sources; or they might report on research conducted outside the United States, and thus are not relevant for our goals; or they do not isolate the impact of residential from nonresidential combustion sources. To focus our attention on the most pertinent materials, we used a combination of automated screening methods (e.g., natural language processing) and manual screening methods. The resulting 2,087 articles prioritized from the bibliographic database searches formed the primary review set for this report, with another 10,606 articles identified as potentially relevant for a future systematic review effort.

Second, we note that 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. We prioritized peer-reviewed references over those retrieved from gray literature sources to help ameliorate this issue.

The large volume of materials collected but not assessed in this report could be 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, we have identified several areas for which a future research effort could leverage these findings through modeling approaches and generate new insights into IRC sources and impacts in the United States.

1 Introduction

1.1. Purpose

The purpose of this project is to assess the state of the research on household combustion appliances and their impacts on indoor and outdoor air quality, climate change, and health in the United States. To our knowledge, no comprehensive review of scientific literature has previously addressed the sources and impacts of U.S. indoor residential combustion (IRC). This report summarizes our review methods and findings. This assessment could inform future advocacy on securing healthy indoor air and reducing the contribution of indoor combustion to regional air pollution and climate change.

1.2. Background

Attention has recently focused on indoor combustion, particularly from the use of natural gas. In 2019, Berkeley, California, became the first city in the United States to ban new gas connections. More than a dozen other cities quickly followed, including several in the Bay Area of California and the Boston, Massachusetts area.[1] In February 2021, Seattle, Washington, banned natural gas for space heating in new commercial and apartment buildings of more than three stories, replacement heating systems in older buildings, and water heating in new hotels, along with energy conservation measures to promote efficient electric heating and cooling systems.[2] In December 2021, New York City became the largest city in the United States to announce plans to phase out fossil fuels in new construction (limited initially to buildings less than seven stories), replacing fossil-fueled stoves, space and water heaters, and other appliances in these uses with electric fueled alternatives, such as heat pumps and induction stoves.[3] New York City had previously banned residual heating oil (No. 6 fuel oil) under its Clean Heat Program in 2016.[4] In May 2022, Los Angeles became the second largest city to join, passing a motion to begin planning for requiring zero carbon emission buildings. Simultaneously, the South Coast Air Quality Management District—which regulates air pollution across much of Southern California, including most of L.A. County—is considering a similar requirement to largely end the sale of space and water heaters fueled by fossil fuel gas along with other types of household appliances (South Coast Air Quality Management Distrct (AQMD), 2022).[5] In reaction to such municipal action, at least 20 states passed “preemption laws” that prohibit local jurisdictions from banning natural gas connections.[6]

Most of this activity is focused on familiar political debates around addressing climate change. Residential and commercial emissions made up 13% of total U.S. global warming emissions in 2020

[1] e.g., “Cities are banning natural gas in new homes, citing climate change,” Irina Ivanova, CBS News, Dec 6, 2019.
[2] e.g., “Seattle City Council passes measure to end most natural gas use in commercial buildings and some apartments,” The Seattle Times, Feb 1, 2021.
[3] e.g., “Is this the beginning of the end of gas stoves and dirty heat in buildings?”, Rebecca Leber, Vox, Dec 16, 2021.
[4] e.g., “NYC's Ban on Heating Oil Helped Clean the Air”, Robert Preidt, US News and World Report, Dec. 8, 2021.
[5] e.g., “L.A. is banning most gas appliances in new homes. Get ready for electric stoves” Sammy Roth, Los Angeles Times, May 27, 2022.
[6] e.g., “Cities tried to cut natural gas from new homes. The GOP and gas lobby preemptively quashed their effort,” Ella Nilsen, CNN, February 17, 2022.

(United States Environmental Protection Agency [EPA], 2022c, 2022d). In 2021, about 83% of the U.S. primary residential fossil energy consumption was from natural gas combustion with the remainder from petroleum consumption, such as heating oil. U.S. households generally do not consume coal directly. Primary energy consumption (i.e., fuels directly consumed in U.S. houses) comprises about 57% of household total energy use in the United States, with the remainder coming from electricity sales. Of the fuels making up U.S. household primary energy consumption, fossil energy is by far the largest share, at about 87%. (United States Energy Information Administration [EIA], Office of Energy Statistics, Office of Energy Demand and Integrated Statistics, Integrated Statistics Team, 2022) The remainder is split among biomass, such as wood (7%), solar (5%), and geothermal (1%).

The concerns over indoor combustion extend beyond climate impacts. Residential energy consumption other than electricity and geothermal energy use is based on combustion. As combustion generally occurs within the building envelope, residents may be directly exposed to combustion byproducts, including nitrogen oxides, carbon monoxide, particulate matter, and a range of toxic air pollutants. Because in the United States roughly 87% of people's lives are spent indoors (Xue et al., 2018), indoor exposure to combustion pollutants has the potential for substantial health effects. Most indoor combustion appliances are vented to the outdoors. In most cases, there is no aftertreatment of the exhaust, implying that indoor byproducts are directly emitted to the outside air, where they contribute to ambient pollution and its health impacts.

1.3. Scope

We focused primarily on assessing peer-reviewed, freely available, scientific literature, written in English, published between 2000 and the present that addresses at least one of the four areas of this research with a specific link to IRC in the United States:

1. IRC-based technologies, fuels, and appliances in use in the United States and their relative prevalence in homes;
2. Emissions from IRC appliances, as designed and as installed and operated. Also, the contribution of IRC to indoor air quality (IAQ), including effect variability by housing type, ventilation system, etc.; interactions with other sources of pollution; and effects of interventions (e.g., air filters, range hoods) to reduce exposure;
3. Contribution of IRC to outdoor air pollution, including criteria air pollutants (CAPs),[7] hazardous (toxic) air pollutants (HAPs),[8] and climate pollution including greenhouse gases (GHGs); and
4. Health impacts of indoor and outdoor exposure to IRC pollutants.

[7] For more information on these pollutants, please see EPA's discussion at https://www.epa.gov/criteria-air-pollutants.
[8] For more information on this class of air pollutants, please see EPA's discussion at https://www.epa.gov/haps.

We supplemented studies from peer-reviewed journals with select reputable gray literature sources, such as government agency websites. We also used information from official government databases and industry publications.

The research areas of interest belong in active broad research domains, such as air quality and climate implications of human activity, environmental health, etc. Accordingly, our bibliographic database and gray literature source searches produced tens of thousands of results. Specifically, we retrieved 70,865 articles from bibliographic database searches (PubMed, EBSCO, Google Scholar) and 9,628 items from 67 potentially relevant web domains (i.e., gray literature sources). Overlaps occur across these results sets, with some articles found by multiple searches and the same articles published in different forms. These counts do not include several articles added post-hoc. However, these values indicate the volume of the material identified.

Systematic (i.e., exhaustive) review of all retrieved articles was not the scope of this project. To bring this volume of material into the original scope of the project,[9] we chose to rely on natural language processing (NLP) methods to prioritize and predict potential relevance of studies to one or more research areas:

- To enable application of NLP methods, we manually assembled a dataset of 1,082 articles that included "seed" studies based targeted literature searches conducted by research area experts and pilot references used for screener training. This dataset was used to fit statistical machine learning models that produced a total of 14,059 unique, potentially relevant articles. These articles were prioritized for manual review based on probabilities assigned by the machine learning algorithms.
- To expand the manually assembled dataset of 1,082 articles, we then screened additional 1,005 references using ICF's litstream tool. This tool employed active machine learning to prioritize articles "on the fly" on the basis of screeners' decisions. As a result, we obtained the primary review set of 2,087 articles from which we have drawn most of our conclusions.
- Finally, we used the 2,087 manually screened articles to train a more advanced machine learning model that was used to re-prioritize the 69,860 remaining unscreened articles (i.e., the remaining 13,054 articles prioritized for litstream screening and 56,806 initially de-prioritized articles). As a result, we obtained 10,606 potentially relevant articles that could be used to support a future systematic review.

We also used gray literature results and additional materials to supplement the peer-reviewed results as necessary, primarily for research areas not well covered by peer-reviewed literature or where sources such as government databases represent the best available information. As such, although our effort to identify and review the most relevant resources was significant, we have not reviewed every possible article that may address these research areas. Furthermore, the literature is

[9]As scoped, the project assumed a maximum of 4,500 references resulting from the peer-reviewed and gray literature searches would undergo initial title-abstract screening, no more than 900 studies would require full-text review, and fewer than 180 studies would undergo synthesis.

constantly evolving as research on these topics progresses.[10] Our research was constrained to articles published within a specific window of time, through early 2022.

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, 10,606 articles prioritized for a future review effort, and gray literature sources compiled for this research, including those retrieved but not prioritized for inclusion in this report.

1.4. Contribution

To the best of our knowledge, this report is the first to consolidate the literature covering four research areas addressing sources and impacts of IRC in the U.S. We identify and synthesize the information collected. We also identify opportunities for future research activities that could build on the work summarized in this report. In addition to the information extracted and reviewed in this report, we provide a relevance-prioritized collection of all articles from bibliographic databases and a collection of all gray literature articles retrieved via the topic-specific searches.

1.5. Organization

This document is ICF's final project report documenting our methods and findings. It is organized as follows:

- Section 2 contains the results of the four IRC research area-specific literature assessments. The findings of each assessment are presented by fuel type: natural gas, other fossil fuels, wood, and other or mixed fuels (including studies that did not distinguish among fuels). Each IRC research area and fuel type-specific subsection contains a summary of findings, followed by an extended analysis of studies selected for review.
- Section 3 discusses the limitations of this assessment.
- Section 4 contains recommendations for future research.
- Section 5 presents references for the sources cited in this report.
- Appendix A summarizes the methods used to search, prioritize, and extract information for this assessment.
- Appendix B contains a complete database of references. This appendix complements Section 5 by providing references for the full set of articles identified as potentially relevant through our searches and the complete set of gray literature identified from the prioritized sources.

[10] For example, days before this report was finalized the Journal of Air and Waste Management Association published a special edition on residential wood combustion [Multiple Authors. (2022). Special Issue on Wood Combustion. *Journal of the Air & Waste Management Association*, *72*(7), 617-790. https://doi.org/10.1080/10962247.2022.2060647]. We were unable to include this in our review due to its release date.

2 Findings

2.1. Indoor Residential Combustion Sources, Appliances, and Fuels

Combustion requires oxygen, and as construction technology has improved, operating combustion appliances within the thermal and pressure boundaries of the home has increased the concerns regarding combustion use within the building envelope due to degraded IAQ and associated residential health impacts. Today's technology allows for a transition from fossil fuel and biomass use in the residential sector to lower emitting, non-combustion alternatives such as electric cooking and heating appliances. About half the homes in the United States use natural gas for space heating and water heating. In 2020, the residential sector accounted for about 15% of total U.S. natural gas consumption, and natural gas was the source of about 23% of the U.S. residential sector's total energy consumption.

This section focuses on the technologies in use for combustion-based appliances in indoor residential use and their relative prevalence in homes, presented by fuel type.

What did we review?

The approach for this section differs from that of the other sections. Few of the "peer-reviewed" articles found were deemed appropriate. Most limited the research to a handful of households and a limited number of devices and do not reflect a population overview. Although a few relevant technical articles were found, most did not extrapolate what was discovered to a substantial portion of the population. Accordingly, the types of residential combustion appliances and their prevalence in homes was largely unaddressed in such articles. We first summarize relevant statistics from the Residential Energy Consumption Survey (RECS) supplemented with data from the American Housing Survey [AHS]. We then address the remaining areas with targeted research from manufacturers and trade organizations (potentially reflecting their inherent biases), gray literature articles, and other peer-reviewed sources.

Beyond heating (kerosene heaters, gas furnaces, gas water heaters, gas clothes dryers, space heaters, and fireplaces) and cooking (gas stoves, gas ranges, gas ovens, wood-burning stoves, coal-burning stoves, and charcoal grills) appliances, other indoor combustion can cause health and exposure issues for residents. Some examples include incense burning, candle burning, tobacco smoke, hobby activities (welding, woodburning, soldering), and outdoor appliances within the building envelope (idling cars, lawn mowers, other activities within enclosed garages). All of these are excluded from our scope.

What are the gaps in research on combustion-based, indoor, residential appliances?

Nationwide data on IRC have been collected for various purposes (e.g., to understand energy consumption in the United States in the case of RECS and U.S. housing stock in the case of AHS). As such, the data collected were not specific to answer the question of the prevalence and impact of IRC. Specific data gaps are identified as follows.

- Robust sources of nationally representative data on IRC were identified and provide an overall description of IRC by fuel type and end use. Few data were identified on the use of decorative appliances, however, particularly alcohol-fueled decorative fireplaces.
- Data were also lacking on the prevalence and use of indoor controls, such as range hoods, or installation methods, particularly vented versus unvented appliances.
- Data was not identified that provided a robust indication of how many of those devices have been installed as designed and how many are failing and spilling combustion gases due to age and lack of maintenance.

2.1.1 Summary

Nearly all (>99.9%) U.S. residences have access to and use electricity. IRC is associated with approximately two-thirds of the approximately 118.2 million housing units in the United States.[11] Over half (~60%) of residences use natural gas, ~15% of homes use other fossil fuels (e.g., propane, fuel oil, kerosene), and 9% of homes use wood, as shown in Figure 1. Generally, IRC increases with owner status and income for all fuel types. A notable exception is higher use of propane in mobile homes versus other housing units. Data that presented prevalence of other sources of IRC (e.g., alcohol fueled decorative appliance, biomass burning) were not identified, either at a national level or in specific (e.g., indigenous) populations.

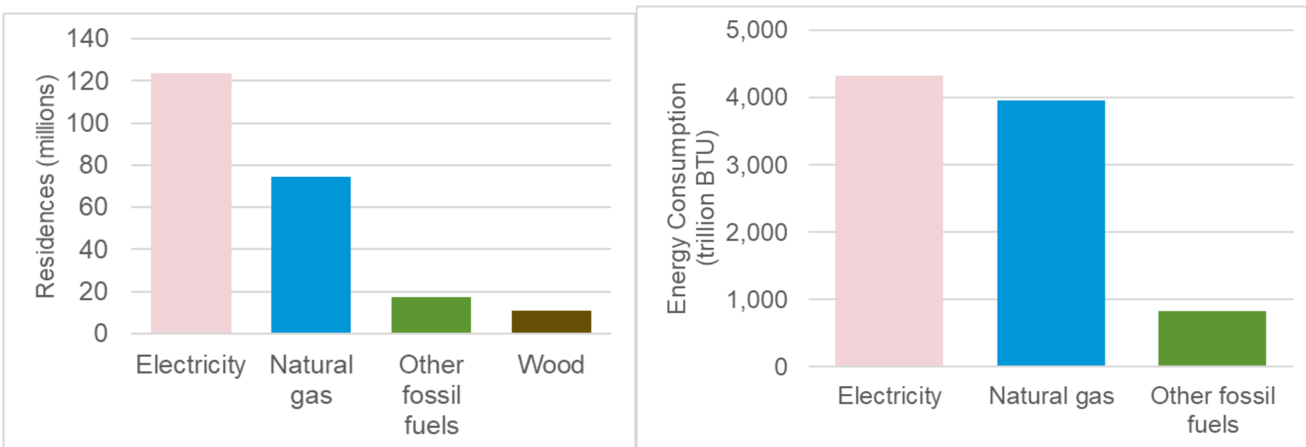
IRC is primarily associated with space heating, water heating, and cooking. Clothes dryers, air conditioners, and decorative appliances (e.g., fireplaces) are also sources of IRC. Sparse data are available on the frequency that IRC appliances are properly installed and operated or the use of engineering controls, such as range hoods or venting (e.g., use of flues.) AHS (2019) reports that one-third of fireplaces do not contain an insert, and are thus directly open to the living space, and approximately three-quarters of a million homes rely on unvented room heaters for primary space heating.

Open indoor combustion (vented and unvented), primarily in the form of natural gas stoves and fireplaces (of any fuel type), is considered to be the primary sources of indoor exposure to products of IRC. Appliances not intended to be vented indoors (e.g., furnaces, clothes dryers) may be commonly assumed to not influence IAQ because the combustion is vented outside of the conditioned building envelope, although some studies do indicate IAQ impacts. For this reason Section 2.2 focuses on the IAQ impacts of IRC resulting from stoves, fireplaces, and heaters but also includes other sources.

[11] RECS provides the following definition of a housing unit: A house, apartment, group of rooms, or single room if it is either occupied or intended for occupancy as separate living quarters by a family, an individual, or a group of unrelated persons. Separate living quarters means the occupants live and eat separately from other persons in the house or apartment and have direct access from the outside of the building or through a common hall—that is, they can get to their unit without going through someone else's living quarters. Housing units do not include group quarters such as dormitories or military barracks.

All IRC contributes to overall emissions to the environment, however, and therefore is associated with decreased outdoor air quality and potential climate change and health impacts. Comparing IRC in this case to electric alternatives is not straightforward without considering upstream emissions, including the source of electricity (e.g., solar versus coal-fired power). Impacts from various fuels are explored in Sections 2.3 and 2.4.

Figure 1. Frequency of Fuel Use in the United States and Associated Energy Consumption



Data source: United States Energy Information Administration [EIA] (2015, 2020).

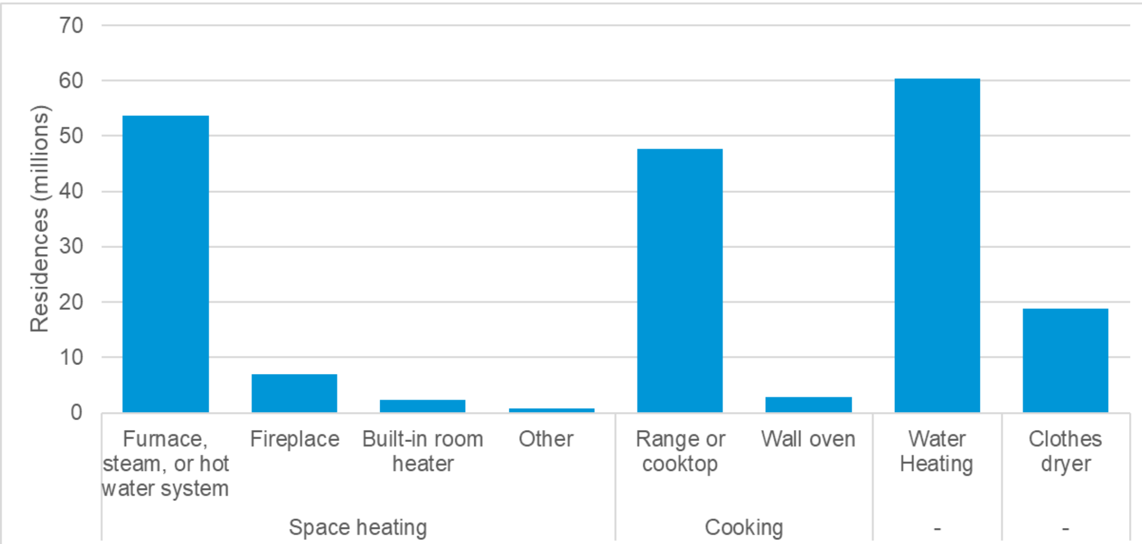
2.1.2 Natural Gas

2.1.2.1 Summary from RECS and AHS

Natural gas is the most common fuel associated with IRC (~85% of households that burn fossil fuels use natural gas). For this reason, we presented it separately from other fossil fuels. Natural gas is primarily used for space heating (~60 million residences), cooking (~40 million residences), water heating (~60 million residences), and clothes drying (~20 million residences). Use of natural gas air conditioning is not presented in RECS; however, AHS reports nearly 2 million homes have natural gas air conditioners. Use of natural gas increases with income and is associated with home ownership; it is used less frequently in rentals and apartments. Versus ~45% of apartments and 35% of mobile homes, 65% of single-family homes use natural gas.

Open natural gas IRC is associated with ~40 million gas stoves or cooktops. Approximately 700,000 households use room heaters without flues (i.e., vented directly to the living space) for their primary heating source. AHS describes these as using natural gas, kerosene, or fuel oil, but fuel type is not specified. Fuel-specific data on the frequency that fireplaces use an enclosure were not identified, however, of all fireplaces, approximately one-third use no insert and thus open directly to the room. Nearly 7 million gas fireplaces are used in the United States. Using this estimator, over 2 million fireplaces with combustion open to the living space could be in use. AHS reports that 72,000 households use a cooking stove (gas or electric) as a primary form of heating, and over 5 million households use a cooking stove as supplemental heating (95,000 were specifically identified as use of a gas oven with the door open.) These are one of the few examples of IRC appliances not being operated as intended, presenting safety and health hazards and potentially altering the emissions profiles.

Figure 2. Landscape of Natural Gas IRC in the United States



Data source: United States Energy Information Administration [EIA] (2015, 2020).

2.1.2.2 Literature Review

What else have government agencies documented?

The U.S. Department of Energy (DOE) (2013) claims, "Space heating is the largest energy expense in the average U.S. home, accounting for about 45 percent of energy bills… The most common home heating fuel is natural gas, and it's used in about 57 percent of American homes."

ENERGY STAR rates a high-efficiency heating system as one that use less energy and operates at reduced noise levels. From the "ENERGY STAR Unit Shipment and Market Penetration Report Calendar Year 2020" by ES partners (2020) market penetration is 59% for residential boilers (57% in the gas market, 77% in the oil market). 59% penetration implies a total market of about 380,000 units shipped in 2020 (roughly 43,000 oil-fueled and 265,000 gas).

What else have industry and academia documented?

In an article by Zachary Merrin and Paul Francisco titled "Unburned Methane Emissions from Residential Natural Gas Appliances" (2019) they describe the methane emissions from 72 location-specific sites in Boston, MA and Indianapolis, IN, "areas where substantial bottom-up research has revealed relatively high and low ambient methane levels respectively" and 28 additional sites with tankless water heaters. The appliances aged on average 10.9 years old. They looked at furnaces, boilers, stoves, range burners, ovens, broilers, and conventional water heaters. One issue that was uncovered in this study was that "per individual unit, tankless water heaters generate the most unburned methane of the tested appliances. Tankless water heaters generate the second highest amount of unburned methane from their ignition spike."

Combustion-based domestic hot water (DHW) systems fall into the realm of installed household appliances. Because these systems are vented, they are defined by the same NFPA venting categories as heating systems with the same levels of spillage. The American Gas Association [AGA] breaks down natural gas water heaters into storage water heaters, combination water/space heaters, tankless or instantaneous water heaters, and indirect water heaters.

According to the Air Conditioning, Heating and Refrigeration Institute [AHRI], "U.S. shipments of residential gas storage water heaters for January 2022 decreased 10.7 percent, to 355,010 units, down from 397,342 units shipped in January 2021. Residential electric storage water heater shipments decreased 1.2 percent in January 2022 to 391,003 units, down from 395,640 units shipped in January 2021."

The Vent Free Gas Products Alliance (2022) reports that "More than 17 million U.S. households use vent-free gas supplemental heating appliances. Vent-free products are fueled by natural gas or propane. The American Gas Association (2022) end of the year report for 2021 states, "Recent analysis shows that we added more than 876,000 new residential customers in the U.S. from 2019 to 2020, the largest increase since 2006!"

What other notable concerns with cooking appliances were identified?

The use of ovens as heating appliances are particularly dangerous and speaks to the difference between appliances used as designed and appliances used as installed. In the CDC's MMWR Weekly from December 26, 1997, Slack and Heumann (1997) refers to the Third National Health and Nutrition Examination Survey (NHANES III) to report that the "number and regional distribution of adults using unvented residential heating appliances and stoves or ovens misused as heating devices in the United States during 1988-1994." During that time unvented combustion space heaters were used by 23.1 million adults. The survey breaks this down further into demographics such as "Stoves or ovens were used for heating in approximately 14.5% of low-income households compared with 6.1% of high-income households." Unfortunately, this study is older than our research window, and a more recent NHANES report of unvented combustion appliances is not available.

Because effluents from cooking with gas stoves and ovens produce particulate matter, range hoods are commonly installed to capture these fumes. Operation of range hoods often depends on the cook who may opt not to use the hood, for noise or other considerations, while pollution control may be a tangential consideration.

2.1.3 Other Fossil Fuels

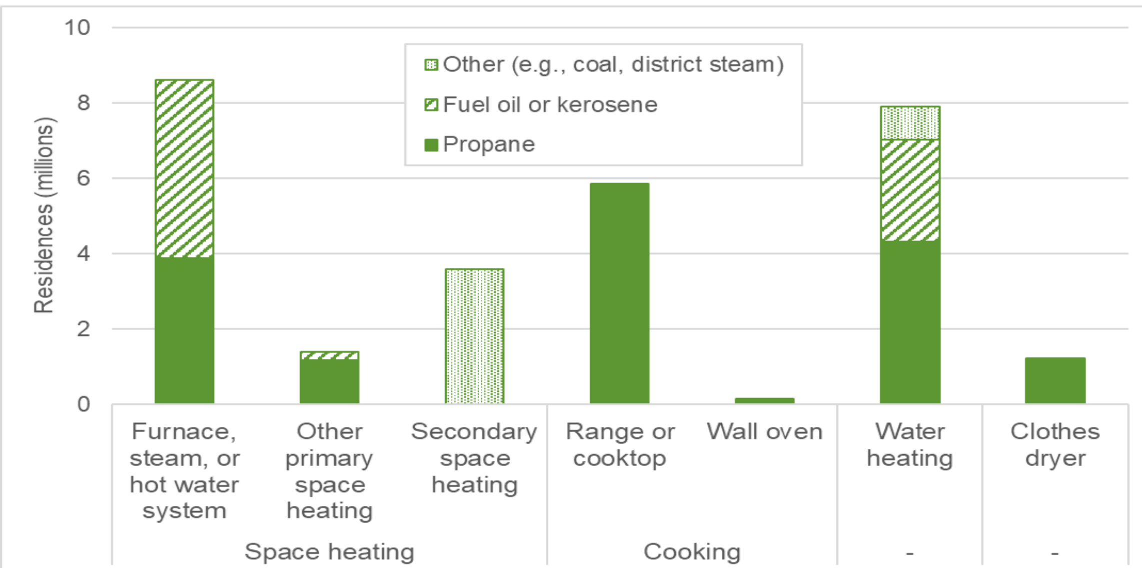
2.1.3.1 Summary from RECS and AHS

Propane dominates the use of other fossil fuels, which also includes kerosene, fuel oil, and coal. Overall, propane is used in 6% of households, but 20% of mobile homes. Propane usage is expected to be more prevalent in rural areas that have no natural gas service. Propane is rarely used in apartments or rentals. Seven million households use fuel oil; of these, approximately 5.7 million use fuel oil for primary heating. Approximately 400,000 households use kerosene for primary heating. Most space heating with these fuels is associated with furnaces and steam or hot water systems. However, 1.4 million households rely on "some other equipment" for primary space heating, which is likely to include some room heaters without flues, as discussed in Section 2.2.3, that are likely to have a larger impact on IAQ.

RECS reports nearly 6 million homes use propane-fueled stoves for cooking. AHS reports an additional 100,000 homes use "other" (unspecified) fossil fuels for cooking.

Propane, kerosene, fuel oil, and coal are all associated with water heating; however, the frequency is much lower than the use of natural gas or electric. Similarly, propane-fueled clothes dryers (1.2 million) and air conditioners (200,000) are also much less common than natural gas or electric alternatives.

Figure 3. Landscape of Other Fossil Fuel IRC in the United States



Data source: United States Energy Information Administration [EIA] (2015, 2020).

2.1.3.2 Literature Review

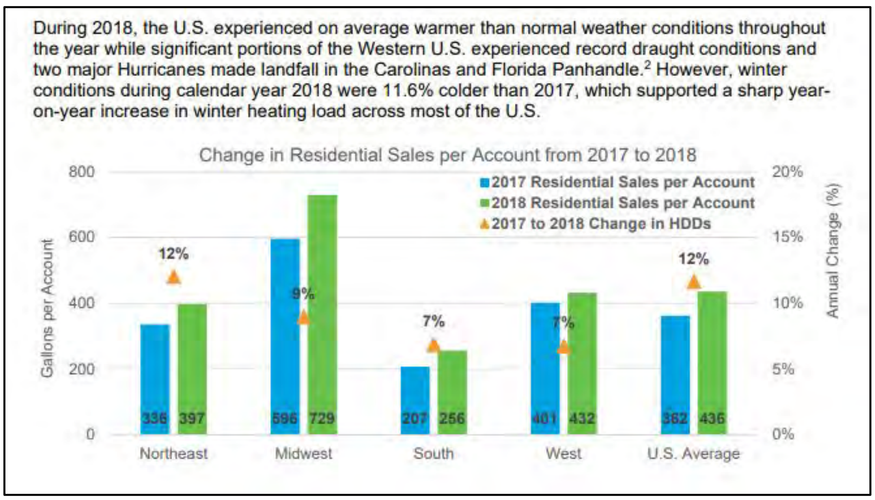
Most of the fossil fuel–fired heating appliances are vented and installed with connecting ducting for conditioned air systems or pipes for hydronic or steam systems. (There are also through-wall systems that are used for spot heating that rely on convective flow through the heater for single room heat supply.) These appliances are divided into categories by the National Fire Protection Association (2021) primarily depending on their venting type. Category I and II systems use negative pressure in their flues to draw out the combustion pollutants and are more susceptible to spillage than Category III and IV systems, which are power vented and sealed combustion systems.

As house construction tightens with the aim at energy savings, issues of combustion spillage increase. This is described by Pigg et al. (2018) in "Impacts of weatherization on indoor air quality: A field study of 514 homes." These appliances are designed to draft naturally, most of them being NFPA rated Category I appliances, reliant upon negative pressure in the flue to guide the combustion gases out of the house. But tightening the house and improving the ventilation systems that rely on putting the house under negative pressure can cause the combustion appliances to backdraft or spill.

What notable regional considerations were identified?

Per RECS (United States Energy Information Administration [EIA], 2022), annual residential heating oil (distillate fuel) consumption by the oil fired furnaces and boilers are more common in the northeast than they are in other parts of the country. The shipments of oil peaked in the 1970's and declined nearly every year since. In the winter of 2020-2021, about 5.3 million households in the United States used heating oil (distillate fuel oil) as their main heating fuel, and about 82% of those households were in the U.S. Northeast Census Region (United States Energy Information Administration [EIA], n.d.).

Figure 4. Regional Residential Propane Sales, 2017-2018



Souce: PERC (2022)

Propane use is also regional. The Propane Education and Research Council (PERC) (2022), which resulted from the Propane Education and Research Act (1996), has in-depth research on the regional uses of propane. (Kuhle & Sloan, 2019) "Nationally, propane is used in 50 million American homes; 11.9 million households rely on propane as their energy source for space or water heating." "The Northeast has the highest share of residential sales, accounting for 60% of total sales, or 877 million gallons." We understand this to mean all uses of propane, including gas grilles, and other outdoor appliances.

What was found on the prevalence of vent-free appliances?

No articles were identified that directly address the question of prevalence in homes for vent-free appliances under Research Area 1. For context, we first present two older studies, noting these are both outside of our research window. We then present two articles noting risks from unvented appliances that note their use and design, and a third counterpoint that includes survey results on their use.

Combustion-based space-heating systems, such as portable unvented kerosene or piped propane heaters, that are portable and unvented may be common in disadvantaged communities because they are inexpensive. The National Ag Safety Database from the University of Missouri Extension from 1993 in an article by David E.

Baker (1993) on unvented portable kerosene heaters states, “The Consumer Product Safety Commission (CPSC) estimates 3,500 heaters were sold in 1974 compared with an estimated 4.5 million in 1982. The CPSC also estimates there may be as many as 9 million kerosene heaters in use in consumers’ homes. Of those, 5.5 million are unvented heaters.”

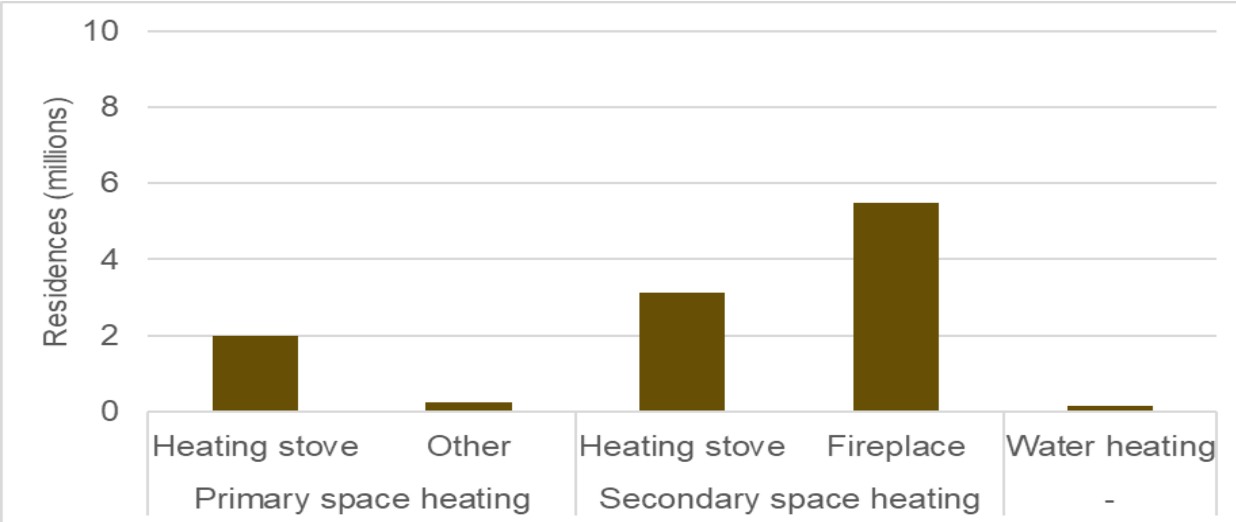
PERC published a paper (Whitmyre & Pandian, 2015), which has been used to advocate for the use of vent free appliances. .This article does not quantify the number of homes containing vent free combustion appliances. It does mention that “in a survey of 35 California homes, Wilson (1999) reported an average burn time of 2.8 hours per use, with a median (50th percentile) of 2.3 hours per use. In most cases, vent-free appliances will only be used for a few hours” in the discussion of the limits on pollutants emitted into the air of the house. The contention is that these are not heating devices and that it “is important to realize that it is impossible to ‘oversize’ a vent-free unit for a given room, because the amount of fuel burned and the amount of heat produced by the vent-free gas appliance will be determined by heat demand on the unit.”

2.1.4 Wood Fuels

2.1.4.1 Summary from RECS and AHS

Wood is less frequently used than electric, natural gas, or other fossil fuels and is most commonly associated with space heating. It is more prevalent in single-family homes (12%) and mobile homes (9%) versus single-family attached homes (3%) or apartments (<2%.) Approximately 5 million homes use a woodstove for either primary or secondary space heating. Woodstoves are enclosed and vented to the outdoor space as opposed to fireplaces that can be directly open to the indoor living space. Fuel-specific data were not identified, but approximately one-third of all fireplaces (regardless of fuel) do not use an enclosure, and while vented via a flue or chimney they are open directly to the living space and are associated with higher indoor emissions. Wood use, particularly fireplaces used as secondary space heating, increases with income and home ownership, suggesting that wood fireplace use is possibly more of a choice of the resident than a necessity.

Figure 5. Landscape of Residential Wood Combustion in the United States



Data Source: United States Energy Information Administration [EIA] (2015, 2020).

2.1.4.2 Literature Review

Solid fuel appliances including coal, wood, and wood pellets are also regional products. There have been numerous studies and code debates regarding the use of these products and their emissions on the air both inside and outside of homes. EPA utilizes this regional distribution to apportion RWC emissions in the NEI (United States Environmental Protection Agency [EPA], 2015), "allocate[ing] wood consumption to the individual county using the relative percent of detached single-family homes in the county to the number of detached single-family homes in the entire climate zone."

Bélanger et al. (2008) conducted a survey on the use of residential wood heating in a context of climate change in the region of Québec, Canada. It found that more than three in four respondents had access to a single source of energy at home, mainly electricity, while 18.5% heated with wood occasionally or daily during the winter. The prevalence of wood heating was higher on the periphery than in more urban areas, and decreased with the prevalence of apartments. It found that neither susceptibility to winter smog, smog warnings in the media, nor belief in human contribution to climate change influenced wood heating practices.

A study generated by the Hearth, Patio, and Barbecue Association (HPBA) by Li et al. (2019) provides the description of the changeout of 260 woodstoves in low-income households in Libby, Montana. This is a report that promotes the work that HPBA is doing in recognizing that products covered by their organization can cause problems in certain situations. In the article they cite a study released by the University of Montana that found that "wood smoke contributed approximately 80% of fine particulate matter in the town's immediate atmosphere." After the changeout of old, uncertified woodstove to new EPA-certified units, the indoor environment improved by about 72% and the outdoor environment by about 28%.

In terms of pellet stove use, the Pellet Fuels Institute (PFI) (2022) says, "There are approximately 1,000,000 homes in the U.S. using wood pellets for heat in freestanding stoves, fireplace inserts, furnaces, grills, and boilers."

2.1.5 Other Fuels

RECS (2015, 2020) includes a description of regional hydronic, or water-based, heating use. It reports that 9.1 million U.S. homes have a hot water or steam hydronic system, although the fuel type is not specified. Of those, 4.8 million are in the very cold/cold climate regions (~52.7% of total us hydronic market), 3.8 million are in mixed-humid climate region (~41.8% of total U.S. hydronic market), 0.3 million are in the mixed-dry/hot-dry climates (~3.3% of total U.S. hydronic market), and ~0.1 million (small sample size) are in both hot-humid and marine climate zones (~2.2% of total us hydronic market).

The University of Minnesota (2010) includes a description of dimethyl ether as a "potential diesel fuel and propane fuel blending agent that is made by the gasification of coal, natural gas or biomass feedstocks." Dimethyl ether derived from biomass feedstocks and other types of biodiesels (Clean Fuels Alliance America, 2022; United States Department of Energy [DOE], 2022) may offer alternatives to petroleum-based fuels in the process of reducing greenhouse gas emissions. Although we found such synthetic fuels as a potential fuel, we have not seen evidence of its use in IRC.

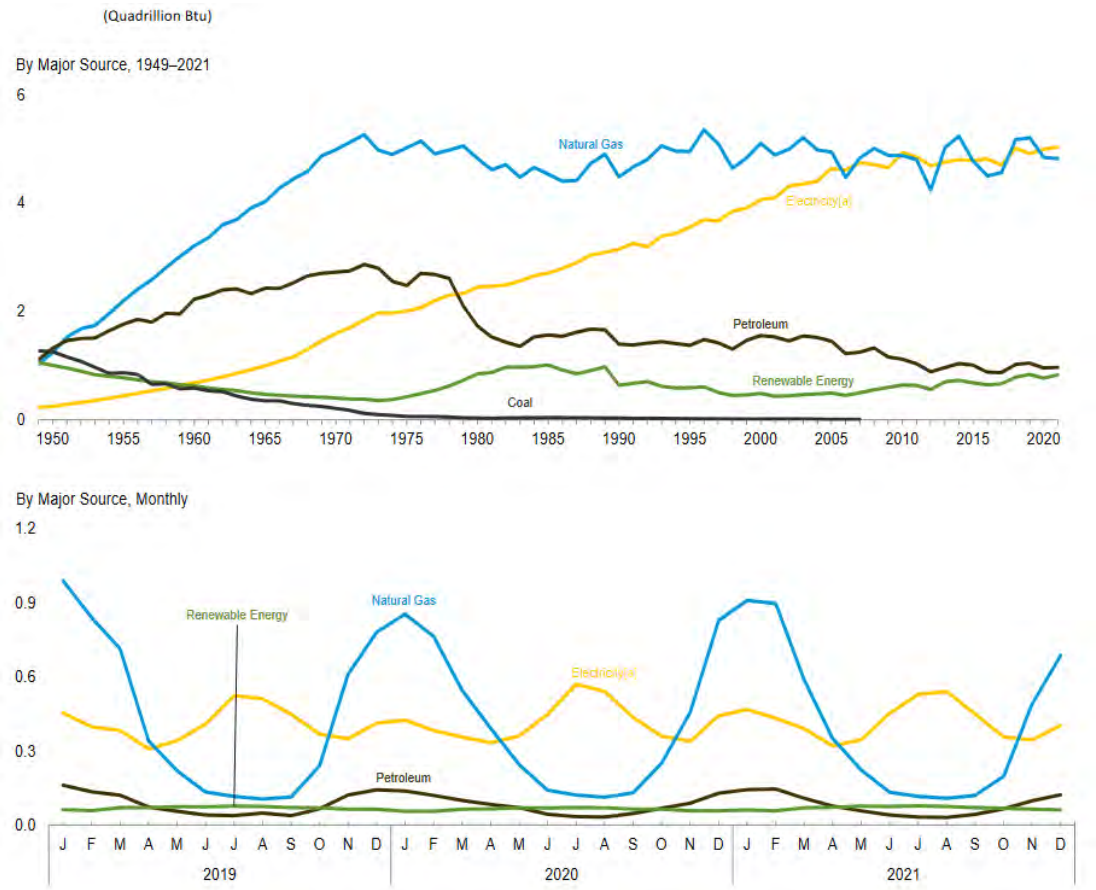
Decorative combustion appliances, such as fireplaces, are frequently unvented. However, the prevalence of use of these devices is not clear. These appliances can be gas- or alcohol-combustion. In a ScienceDaily article from Fraunhofer-Gesellschaft, titled "Ethanol Fireplaces: The underestimated risk," Fraunhofer-Gesellschaft (2014) writes about the increasing popularity of these devices. "Go to the DIY-market in the morning, buy the fireplace, and that evening, enjoy the cozy warmth and homey atmosphere of your new ornamental hearth." They do not provide information on the number of these units in homes.

2.1.6 Trends in Residential Energy and Fuels

2.1.6.1 Summary from RECS

Figure 6 shows annual total residential sector energy consumption for natural gas, other petroleum fuels, electricity, renewable energy, and coal since 1949 in the top panel. The bottom panel shows the seasonality of this energy consumption over the past three complete years.

Figure 6. Residential Sector Energy Consumption, from RECS



Source: RECS Table 2.2. Energy consumption by sector. https://www.eia.gov/totalenergy/data/monthly/#consumption.

2.1.6.2 Literature Review

The Air Conditioning, Heating and Refrigeration Institute (2022) releases monthly shipping data of combined U.S. manufactured shipments of central air conditioning, air-source heat pumps systems, gas and oil furnaces, and gas and electric tank water heaters. These monthly reports extend back to 2010 up to February 2022. compares the number of units shipped in January 2009 to January 2022. According to AHRI, the number of gas water heaters shipped for January 2022 decreased 10.7 percent, to 355,010 units down from 397,342 units shipped in January 2021.

Table 1. Comparison of Combustion Equipment Shipment in January 2009 and January 2022 (No. of units)

Device	January 2009	January 2022
Oil Warm Air Furnaces	3,186	2,791
Gas Warm Air Furnaces	134,370	306,853
Residential Gas Water Heaters	299,448	355,010

Data source: AHRI (2022)

2.2. IRC Appliance Emissions and Contribution to IAQ

This section addresses the scale of emissions from IRC and the resulting impacts on IAQ, for CAPs like CO, NOx, and PM as well as HAPs like VOCs and PAHs. Consistent with the project's scope, our focus was on appliances and fuels used in the U.S. IRC can emit many pollutants into the home, sometimes resulting in high indoor concentrations of those pollutants. Literature on gas IRC mostly was focused on kitchen appliances because of their frequency of use, proximity to the user, and lack of automatic ventilation; attention was focused mostly to CO, NOx compounds, and PM. Other gas appliances like heaters/boilers/furnaces and water heaters are less well studied; the existing literature suggests relatively high emissions, although venting reduces their impact on IAQ. Other fossil fuels are even less represented in the literature. RWC literature often was focused on issues with outdoor/ambient air quality, so the literature we reviewed regarding indoor RWC issues mostly pertained to emission rates rather than the resulting IAQ issues. RWC literature focused most heavily on CO, PM, and PAHs.

We also note that the United States does not have residential indoor air quality standards or guidelines. U.S. EPA does not regulate indoor air, although other agencies have developed recommended thresholds specifically for indoor occupational exposures. Ambient (outdoor) guidelines may not be applicable to indoor exposures. On the one hand, peak indoor concentrations of air pollutants generated by indoor sources (e.g., $PM_{2.5}$, NO_2) may be higher than outdoors, while for other pollutants indoor concentrations may be lower (e.g., ozone, SO_2). On the other hand, duration, activity, and temporal patterns of exposure and air pollutant co-exposures are likely different indoors and outdoors. Additionally, for PM, size and chemical composition may differ indoors from outdoors and this may influence associated health effects (Mitchell et al., 2007; Rokoff et al., 2017; Schwartz et al., 2020). Internationally, both the World Health Organization and Health Canada have established guidelines for specific indoor air pollutants, considering potential detrimental health effects from long-term and short-term exposure to those pollutants. For reference, we include Health Canada's residential air quality guidelines for selected pollutants most relevant for IRC in Table 2. Fine particulate matter ($PM_{2.5}$) was not included in the most recent guidelines, due to the absence of an identified threshold for its health effects, but Health Canada recommended that "indoor $PM_{2.5}$, at a minimum, be lower than $PM_{2.5}$ outside the home."

Table 2. Health Canada's Residential (Indoor) Air Quality Guidelines for Selected Pollutants

Air pollutant	Maximum Exposure Limit	
	Long-term exposure limit	Short-term exposure limit
Acrolein[a]	0.44 μg/m³ (0.19 ppb), 24-hour	38 μg/m³ (17 ppb), 1-hour
Carbon monoxide (CO)[b]	11.5 mg/m³ (10 ppm), 24-hour	28.6 mg/m³ (25 ppm), 1-hour
Nitrogen dioxide (NO_2)[c]	20 μg/m³ (11 ppb), 24-hour	170 μg/m³ (90 ppb), 1-hour
Formaldehyde[d]	50 μg/m³ (40 ppb), minimum 8-hour average	123 μg/m³ (100 ppb), 1-hour average

[a] Source: Health Canada (2021)

[b] Source: Health Canada (2010)

[c] Source: Health Canada (2015)

[d] Source: Health Canada (2006)

What did we review?

We focused on the emissions profiles and resulting IAQ issues of IRC equipment. We present results by fuel type. We also discuss air cleaners/filtration/exhaust, weatherization, and disproportionate socioeconomic impacts where such information was available. We integrate discussions of emissions with discussions of IAQ.

Our summary of IRC emissions profiles concerns emissions both as designed and as installed and operated. For the topic of appliance emissions profiles, we reviewed the full text of approximately 53 papers we identified as potentially relevant during title-abstract screening (29 were peer-reviewed papers; 24 were papers from gray literature). From this literature, we identified 25 peer-reviewed papers and 3 papers from gray literature relevant to this topic. In this section, we synthesize some of the important findings from each of these 28 relevant papers.

Our summary of IAQ from IRC includes variables such as housing type, ventilation, and the potential effects of interventions (such as air cleaners and range hoods) to reduce IAQ issues. We reviewed the full text of approximately 63 papers that we identified as potentially relevant during title-abstract screening (40 were peer-reviewed papers and 23 were papers from gray literature). We identified 29 peer-reviewed papers and 9 papers from gray literature relevant to this research area. In this section, we synthesize some important findings from each of these 38 relevant papers.

2.2.1 Summary

What do we know about appliance emissions profiles and IAQ impacts?

Gas kitchen appliances, and RWC in general, were relatively well studied in the reviewed literature, while other appliances (gas clothes dryers, gas water heaters, gas or kerosene space heaters, and fireplaces) were discussed in relatively few papers. Several papers discussed the impacts on IAQ from use of kitchen exhaust fans or other indoor air cleaners or ventilation, although only a couple papers discussed the impacts of weatherization on IAQ. A few papers discussed potential disparities in IAQ across socioeconomic boundaries.

IRC emits a suite of CAPs and HAPs, at levels depending on appliance age, maintenance status, operator behavior, usage setting or intensity, and fuel type, among other factors. The impacts on IAQ can depend on whether the appliance is vented, how often the appliance is on, and how the appliance is used. Emission factors derived from laboratory or idealized settings often substantially underestimate the emission factors achieved in real-world scenarios.

Gas kitchen appliances can emit large amounts of CO and NOx and notable amounts of PM. The IAQ impacts can extend well beyond the kitchen, particularly when exhaust fans are not used (they often are not used or are used inconsistently). Relative to gas stoves and ovens, gas clothes dryers may emit PM at similar levels but have a smaller impact on IAQ, while gas heaters and especially gas water heaters can create considerably higher emissions. IRC using propane and especially kerosene emits at higher rates than using natural gas. These emissions and resulting impacts on IAQ would be significantly mitigated by switching to electric appliances.

Although relatively few studies analyzed the IAQ impacts of RWC, they found generally that such appliances can substantially impact IAQ (e.g., CO, NOx, PM, and HAPs), sometimes beyond the room where combustion occurs, but this can be mitigated with newer and closed-door appliances. Many more studies examined the emissions from RWC, although few separated the impacts by type of appliance. Emission factors from wood, biomass, and pellets can vary widely, depending on appliance age and maintenance, operator behavior, and exact fuel type. Pellet fuels generally emit at lower levels than wood fuels, although the type of pellet is a large factor. Hot starts generally emit less than cold starts, and the normal combustion/flaming phase generally emits less than smoldering phases.

Some indoor air cleaners can be quite effective at removing pollutants after they are emitted by IRC, while weatherization/energy efficiency efforts can have a mixed impact on IAQ in homes. Households of lower socioeconomic status, including multifamily housing, tend to be more influenced by indoor sources due to occupant density and inadequate ventilation.

What are the gaps in research on appliance emissions profiles and IAQ impacts?

Additional measurements should be collected regarding emissions and resulting IAQ impacts from gas clothes dryers, furnaces and boilers, water heaters, and fireplaces. The body of knowledge also may benefit from additional monitoring of HAPs—although the reviewed literature contains some information on PAHs and VOCs, additional measurements of those and other HAPs would be useful. The IAQ impacts from RWC in U.S. settings also were not well represented in the reviewed literature.

2.2.2 Natural Gas

2.2.2.1 Summary

In this section, we cite information on emission rates or impacts on IAQ from IRC with natural gas, from approximately 28 papers or reports. Kitchen appliances were relatively well studied, while other appliances (clothes dryers, water heaters, fireplaces, space heaters, etc.) were less studied.

IRC with natural gas is known to emit pollutants like CO, NO_2, NOx, PM, and HAPs like PAHs, and as a result they increase the indoor concentrations of these pollutants. The amount emitted or the impact on IAQ can be highly variable, depending on things like the appliance age, maintenance status, operator behavior, usage time and intensity, vented versus unvented status, room or house ventilation, etc.

For kitchen appliances, gas stoves and ovens may emit between 100,000 and 200,000 µg/hr of NO_2, 100,000s of µg/hr of CO and NOx, and on the order of 10^{12}–10^{13} particles/min of PM. These emissions can lead to peak concentrations in the kitchen at or above 1,000 µg/m^3 NO_2, 6,000 µg/m^3 NOx, 18,000 µg/m^3 CO, and on the order of 10^4 particles/cm^3 of PM, depending on the number of stove burners being used, whether the both the stove and oven are in use, the length of time the appliance is used, and other factors. These emissions can noticeably impact IAQ in other areas of the house. When the appliance is on but no food is being cooked, emissions of these pollutants are higher from gas appliances than from electric appliances.

The impact of kitchen exhaust fans on IAQ (i.e., the ability of fans to remove pollutants emitted indoors from gas kitchen appliances) can vary widely, depending on fan speed, fan configuration (particularly if it exhausts to the outside), burner usage, etc., and many people either do not typically use their fans or they use them sub-optimally. With proper usage, fans have been shown to significantly reduce peak concentrations of ultrafine PM. Additional filtration units or air cleaners may also be effective in removing IRC-generated emissions.

Gas heaters, and more substantially gas water heaters, have considerably higher emission rates of some pollutants relative to gas kitchen appliances, emitting potentially 1,000,000s of µg/hr CO and NOx, and 100,000s of µg/hr NO_2. Gas clothes dryers may emit PM at similar rates as gas kitchen appliances but perhaps having a somewhat smaller impact on indoor PM air quality. Unvented gas fireplaces may increase indoor concentrations by 10s of ppm CO but perhaps at or below 1 ppm NO_2 and around 35 µg/m^3 PAHs, depending on the fireplace setting and length of usage. Heating with electric appliances produces fewer emissions.

2.2.2.2 Literature Review

Are there guidelines and safety standards for gas appliances?

In a 2016 publication (Building Performance Institute, 2016), the Building Performance Institute (BPI) cited guidelines for safety inspections of vented gas appliances, with CO thresholds in flue gas as follows (where "air free" means that air not used in combustion is removed from the concentration calculation):

- 400 ppm air free for central furnaces, floor and gravity furnaces, direct-vent wall furnaces, boilers, clothes dryers, and gas logs (the latter for those installed in wood-burning fireplaces, where the measurement is in the firebox)
- 200 ppm air free for BIV wall furnaces, room heaters, and water heaters
- 225 ppm as measured for ovens and broilers
- 225 ppm as measured for gas logs in a gas fireplace (measured in vent) and refrigerators.

Furnaces, boilers, and domestic hot water heaters are subject to consumer safety certifications that are required by building codes. Underwriters Laboratories, Electrical Testing Laboratories, MET Laboratories, and CSA International have certification specifications for combustion appliances (not otherwise cited or reviewed here). The Air-Conditioning, Heating, and Refrigeration Institute provides the performance certifications for each device and each model used in the Residential Energy Services Network's home energy ratings. These are the "as designed" numbers (not otherwise cited or reviewed here).

What has been found regarding gas appliance emissions and impacts on IAQ?

ASHRAE (2012) reviewed several studies (mainly Singer et al. (2009); Traynor et al. (1996)) of unvented IRC, and while they did not re-state quantitative values, some of their findings were as follows: (1) one study, using lab tests, found gas burners had NOx emissions that were similar to gas ovens and broilers, but higher emissions of CO and $PM_{2.5}$ and lower emissions of formaldehyde; and, (2) another study, using lab and field tests, found widely varying emissions across and within burner groups and burner operation mode, but generally: (a) gas broilers had lower NOx and CO emissions relative to gas cooktop burners and ovens (although some burners and ovens also had low CO emissions), (b) burners had higher NO_2 emissions, (c) ovens had higher formaldehyde emissions, and (d) broilers had the highest PM emissions (with ovens having the least).

Compared to ASHRAE (2012), Zhu et al. (2020) employed a deeper analysis of existing literature and then utilized regression modeling to estimate emission factors for gas appliances, with a focus on representing real-world scenarios in California. We show in Table 3 the emission rates they found, indicating higher emission rates from gas ovens than gas stoves (particularly for CO and NOx), with substantially higher emission rates of NO_2 and NOx from gas heaters than ovens and stoves, and, beyond that, much higher rates of all three pollutants from gas water heaters. Tankless gas water heaters had significantly higher emissions of CO and formaldehyde (not shown) than storage heaters. They note that emission factors (e.g., units of mass of pollutant emitted per unit energy generated) generally were shown to decrease over time as technology advanced, although with appliances designed to be vented (e.g., gas heaters and water heaters) there was some evidence of significant increases in NOx emissions. The authors then used modeling to estimate indoor concentrations of CO, NO_2, and NOx emitted from kitchen appliances, which we show in Table 4 for average peak concentration (in the kitchen) and average time-weighted concentration (whole-house), with range hoods not used for venting. While there are no U.S. IAQ standards for these pollutants, for reference the authors note that the modeled average peak NO_2 concentrations exceed Canada's 1-hour Health Canada Residential IAQ Guidance level (170 $\mu g/m^3$). The time-weighted averages after 15 minutes of cooking were considerably lower than the peak averages, but these time-weighted averages were notably higher after 2 hours of cooking (three to five times higher; not shown) when NO_2 levels for gas stove + gas oven reached 64 $\mu g/m^3$, which for reference exceeds the Health Canada Residential IAQ Guidance level for 24-hour exposure (20 $\mu g/m^3$; note that 1 hour of cooking led to an average modeled NO_2 concentration of 34 $\mu g/m^3$, also exceeding the Canadian guidance level). Figure 7 is from Zhu et al. (2020) and indicates modeled peak kitchen CO and NO_2 concentrations; while U.S. and California ambient (outdoor) air quality standards do not apply to indoor exposures (see discussion in Section 1.2), and 1-hour-average standards do not apply to peak concentrations, the authors display those levels for reference only.

Table 3. From Selected Studies: Sample of Emission Rates from Appliances Powered by Natural Gas

Study	Appliance Type	Emission Rate (mean unless otherwise stated)				Notes
		CO	NO_2	NOx	PM	
Zhu et al. (2020)	Gas stove	670,000 µg/hr	130,000 µg/hr	440,000 µg/hr	NA	Derived from literature search and regression modeling; focus on California real-world scenarios
	Gas oven	1,700,000 µg/hr	150,000 µg/hr	640,000 µg/hr	NA	
	Gas heater	1,300,000 µg/hr	320,000 µg/hr	1,600,000 µg/hr	NA	
	Gas water heater	3,200,000 µg/hr	490,000 µg/hr	2,300,000 µg/hr	NA	
Wallace et al. (2008)	Gas stove	NA	NA	NA	• Range 4.6×10^{12} – 13×10^{12} particles/min (no food cooking) • Range 0.4×10^{12} – 7.0×10^{12} (cooking food or boiling water)	Derived from concentrations measured in bedroom (U.S. locations)
	Electric stove (for comparison)	NA	NA	NA	• Range 0.6×10^{12} – 11×10^{12} particles/min (no food cooking) • Range 0.14×10^{12} – 14×10^{12} (cooking food or boiling water)	
	Gas oven	NA	NA	NA	• Range 0.3×10^{12} – 5.1×10^{12} particles/min (no food cooking) • Range 0.4×10^{12} – 1.1×10^{12} (cooking food)	
	Electric oven (for comparison)	NA	NA	NA	Range 0.06×10^{12} – 0.8×10^{12} particles/min (no food cooking)	
	Electric toaster oven (for comparison)	NA	NA	NA	• Range approx. 3×10^{12} – 6×10^{12} particles/min (no food cooking) • Range 1.8×10^{12} – 3.7×10^{12} (cooking food)	
Wallace & Ott (2011)	Gas stove	NA	NA	NA	• 1.89×10^{12} particles/min (cooking various foods) • Range $< 0.5 \times 10^{12}$ to $> 4 \times 10^{12}$ particles/min (no food cooking)	Measured; limited U.S. field studies
	Gas clothes dryer	NA	NA	NA	4.40×10^{12} particles/min	
	Fireplace (fuel type not specified)	NA	NA	NA	0.003×10^{12} particles/min	
	Space heater (fuel type not specified)	NA	NA	NA	0.13×10^{12} particles/min	
Dutton et al. (2001)	Unvented gas fireplace	Range <1 (low setting) – 11 g/hr (medium or high setting)	NA	NA	NA	Two Colorado homes

Notes: CO = carbon monoxide; NO_2 = nitrogen dioxide; NOx = nitrogen oxides; PM = particulate matter; µg = micrograms; hr = hour; g = gram; NA = not addressed by the study.

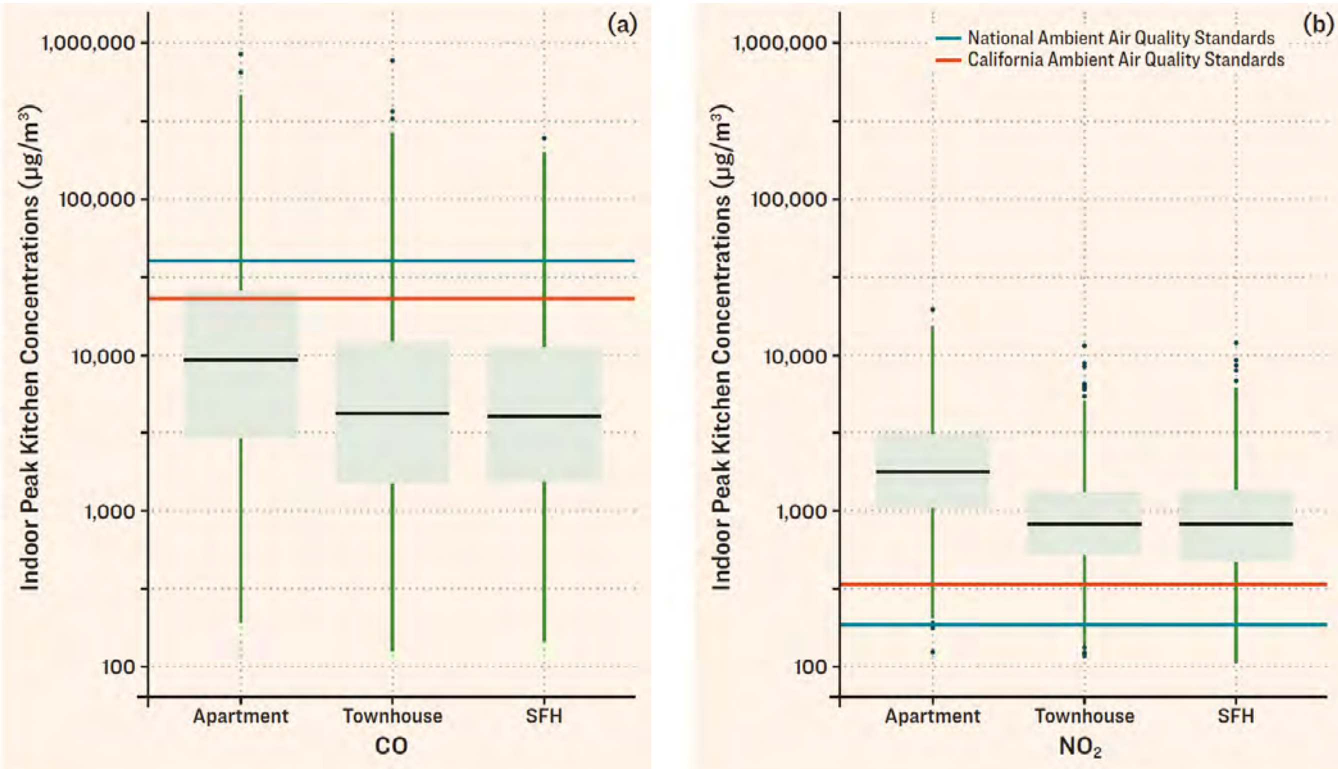
Table 4. From Selected Studies: Sample of Indoor Air Concentrations from Emissions from Appliances Powered by Natural Gas

Study	Appliance Type	Indoor Concentration (mean unless otherwise stated)						Notes
		CO	NO_2	NOx	NO	PAH	PM	
Zhu et al. (2020)	Gas stove	• 5,600 µg/m³ (average peak in kitchen) • 550 µg/m³ (average time-weighted, whole house)	• 750 µg/m³ (average peak in kitchen) • 12 µg/m³ (average time-weighted, whole house)	• 2,800 µg/m³ (average peak in kitchen) • 26 µg/m³ (average time-weighted, whole house)	NA	NA	NA	Modeled using emission factors from derived from literature search and regression modeling; focus on California real-world scenarios and assumes no use of range hoods; average time-weighted modeled concentrations reflect whole-house concentrations after 15 minutes of cooking time
	Gas stove + Gas oven	• 18,000 µg/m³ (average peak in kitchen) • 950 µg/m³ (average time-weighted, whole house)	• 1,600 µg/m³ (average peak in kitchen) • 16 µg/m³ (average time-weighted, whole house)	• 6,700 µg/m³ (average peak in kitchen) • 43 µg/m³ (average time-weighted, whole house)	NA	NA	NA	
Wallace & Ott (2011)	Gas stove	NA	NA	NA	NA	NA	• Range 67x10³ – 88x10³ particles/cm³ (boiling water on one burner) • Maximum > 100x10³ (cooking various foods)	1-hour averages
	Gas oven	NA	NA	NA	NA	NA	• Range 52x10³ – 129x10³ particles/cm³ (no food being cooked) • Maximum > 300x10³ (cooking various foods)	
	Gas clothes dryer	NA	NA	NA	NA	NA	Range 16x10³ – 50x10³ particles/cm³	
	Fireplace (fuel type not specified)	NA	NA	NA	NA	NA	0.14x10³ particles/cm³	

Study	Appliance Type	Indoor Concentration (mean unless otherwise stated)						Notes
		CO	NO_2	NOx	NO	PAH	PM	
Dutton et al. (2001)	Unvented gas fireplace	• Range approx. 2 (low setting) – 78 ppm (medium or high setting) • Maximum > 128 ppm	Range 0.09 (low setting) – 0.36 ppm (medium or high setting)	NA	NA	35 μg/m^3 (cumulatively sampled across fireplace settings)	NA	Two Colorado homes; time-weighted averages with measurement times varying between 0.8 hr and 9.1 hr
Francisco et al. (2010)	Unvented gas fireplace	• <18 ppm (maximum 1-hour average) • Range approx. 1 – 15 ppm (maximum 8-hour average)	Range <100 – 1,288 ppb (maximum 1-hour average)	NA	NA	NA	NA	Illinois homes
Dennekamp et al. (2001)	Gas stove	NA	• Maximum 996 ppb (4 burners) • Maximum 437 ppb (1 burner)	NA	• Maximum 2060 ppb (4 burners) • Maximum 572 ppb (1 burner)	NA	• 14.6x10^4 ultrafine particles/cm^3 (4 burners) • 2.6x10^4 ultrafine particles/cm^3 (1 burner) • 59x10^4 ultrafine particles/cm^3 (frying bacon)	5-minute peak ultrafine PM after 15 minutes of cooking
	Electric stove (for comparison)	NA	NA	NA	NA	NA	• 11.1x10^4 ultrafine particles/cm^3 (4 burners) • 9.4x10^4 ultrafine particles/cm^3 (1 burner) • 15.9x10^4 ultrafine particles/cm^3 (frying bacon)	
	Gas oven	NA	Maximum 230 – 373 ppb (various foods)	NA	Maximum 627 – 1067 ppb (various foods)	NA	Range 9.8x10^4 – 12.5x10^4 ultrafine particles/cm^3	
	Electric oven (for comparison)	NA	NA	NA	NA	NA	Range 1.6x10^4 – 3.0x10^4 ultrafine particles/cm^3	

Notes: CO = carbon monoxide; NO_2 = nitrogen dioxide, NOx = nitrogen oxides; NO = nitric oxide; PAH = polycyclic aromatic hydrocarbons; PM = particulate matter; μg = microgram; m^3 = cubic meter; cm^3 = cubic centimeter; ppb = parts per billion; ppm = parts per million; hr = hour; NA = not addressed by the study.

Figure 7. Modeled Peak Kitchen Carbon Monoxide (CO) and Nitrogen Dioxide (NO_2) Concentrations



Source: Zhu et al. (2020).

Distributions of peak modeled concentrations in the kitchen resulting from usage of gas-powered unvented stoves and ovens (without use of range hoods), relative to the 1-hour ambient (outdoor) air quality standards, by housing type (apartment, townhouse, and single-family home [SFH]) and pollutant: (a) CO and (b) NO_2. Note that peak concentrations are not properly comparable to 1-hour-average concentrations, nor are indoor concentrations properly comparable to ambient standards (see discussion in Section 1.2).

While Zhu et al. (2020) did not monitor for PM, three monitoring studies by Wallace (2006; 2011; 2008) did so in U.S. locations. Wallace (2006) did lengthy PM monitoring in a Virginia house. They found basic cooking and clothes drying led to peaks in particle numbers at smaller sizes (larger sizes for more complex cooking or cooking with electric appliances), and PM concentrations were relatively high for complex cooking, and certainly the kind of food and cooking had a notable impact on all these observations. Wallace et al. (2008) evaluated gas kitchen appliances, along with electric appliances for comparison. They derived emission rates from measurements in the bedroom about 12 m away from the kitchen (due to the kitchen monitor being too close to the emission source), which, along with particle coagulation, could result in underestimation of emission rates. They found that when no food was being cooked, emission rates generally were highest from gas stoves, followed by electric stoves, electric toaster ovens, gas ovens, and finally electric ovens, although with overlaps in the ranges of emission rates (see Table 3). When food was being cooked, emission rates generally were highest from electric stoves, followed by gas stoves, electric toaster ovens, and finally gas ovens (electric ovens not evaluated while cooking food), again with substantial overlap in ranges. The authors also noted that room-to-room PM gradients do not last long due to air exchange within the home. Wallace & Ott (2011) focused on gas kitchen appliances, and one notable finding was that burner emission rates varied widely even when nothing was being cooked (see Table 3), depending on burner usage and configuration and what cookware was on the burner; emissions sometimes were higher without food cooking than with food cooked. Measurements of 1-hour PM concentrations from gas stoves and ovens (see Table 4) were uncertain, with confounders for what if anything was being cooked or what empty cooking container was used. They found generally higher PM concentrations from gas ovens than gas stoves (although concentrations from a stove boiling water on two burners were roughly twice as high as with one burner; not shown), and generally higher concentrations when food was being cooked versus when the appliance was simply on. Their concentration measurements indicated that when gas kitchen appliances were in use, PM concentrations were several times higher in the kitchen than in other areas of the house. They also derived PM emission rates (Table 3) and 1-hour-average PM concentrations (Table 4) for gas clothes dryers (a substantially higher emission rate than for gas stoves, but resulting in generally lower concentrations); for fireplaces and space heaters, although they were not clear on the fuel type being used, both had substantially lower emission rates than gas stoves (particularly for the fireplace).

Additional measurements from unvented gas fireplaces, in two Colorado homes, were available from Dutton et al. (2001), who found emissions of several PAHs and highly variable CO emissions, the latter likely due to variations in gas inlet pressure or lack of maintenance and possibly related to the high elevation. CO emissions (see Table 3) and indoor concentrations (see Table 4) spanned over an order of magnitude depending on the fireplace setting, while the range of concentrations was smaller but still substantial for NO_2. Further, Francisco et al. (2010) made concentration measurements of unvented gas fireplaces in Illinois homes and found some homes' maximum 8-hour-average CO values were above 10 ppm and/or maximum 1-hour-average NO_2 values were above 500 ppb, with extended appliance usage particularly affecting CO levels.

While switching from gas-powered to electric-powered appliances generally will reduce indoor emissions and improve IAQ, gas-powered kitchen appliances are an improvement upon biomass cookstoves when it concerns PM. Gas cooking appliances can reduce indoor $PM_{2.5}$ levels potentially by 100s of µg/m3 relative to biomass cookstoves (Shupler et al. (2018) observed mostly in developing countries). Similarly, Zenissa et al. (2020) observed in Indonesia that gas cooking significantly reduces indoor $PM_{2.5}$ concentrations relative to cooking with wood.

Dennekamp et al. (2001) also characterized PM emissions from cooking experiments where the gas combustion was the most important source of PM, and they found that most particles were 15–40 nm in size, with larger particles (50–100 nm) produced during frying bacon. Particles grew in size over time due to coagulation, and electric cooking also produced ultrafine PM.

In a study initiated by the Propane Education & Research Council (PERC), Whitmyre & Pandian (2015) used Monte Carlo modeling of vent-free gas appliances in energy-efficient homes to estimate that indoor concentrations across 99.9-100% of U.S. simulations were below 9 ppm CO and 0.110 ppm NO_2. On the contrary, Logue et al. (2014) used modeling to estimate that cooking with natural gas (and without exhaust fans, which commonly is done in typical California homes) routinely produced 1-hour indoor NO_2 concentrations above 100 ppb (0.1 ppm), constituted an average of 30% of the indoor CO concentrations (routinely above 5 ppm during winter), and routinely produced formaldehyde levels above 25 ppb (1-hour average) and 2 ppb (1-week average during winter).

Finally, radon often is not discussed as a contaminant associated with gas appliances, but Mitchell et al. (2016) estimated that indoor radon concentrations from use of natural gas appliances (particularly gas originating from Marcellus shale in the United States) are quite low relative to EPA action levels.

Have additional comparisons been made between gas appliances and electric ones?

Yes, for example:

- Favarato (2015) reviewed many studies and found much evidence that cooking and home heating with gas appliances led to higher NO_2 concentrations than when using electric.

- Dennekamp et al. (2001) made a similar observation for cooking appliances, finding electric cooking produced no additional NOx while gas cooking produced large peaks in indoor NO and NO_2, with four burners producing about twice the levels of NO_2 and about four times the levels of NO (see Table 4) as with one burner. They also measured ultrafine PM concentrations from gas and electric stoves and ovens, finding substantially lower emissions from electric ovens relative to gas ovens and generally lower emissions from electric stoves versus gas stoves.

- Similarly, Seals & Krasner (2020) cited a study finding that replacing gas stoves with electric stoves substantially reduces NO_2 levels across the house.

- Also, Mullen et al. (2016) found that gas cooktops lead to substantial increases in indoor concentrations in the kitchen (for NOx, NO_2, and CO, with NO_2 levels occasionally exceeding 30 ppb, and CO levels usually below 20 ppm) and in other areas of the house (NOx and NO_2), particularly with longer cooking times (a trend not observed with electric appliances) and particularly when kitchen exhaust fans were not used. Appliance age and the use of pilot burners might have played a role in these observations, although the size of the house (and its air-exchange rates) can be confounding. They did not observe a relationship between gas cooking and indoor levels of formaldehyde and acetaldehyde. Mullen et al. (2012) similarly found a strong association between use of gas appliances (particularly cooking appliances) and higher indoor levels of NOx and NO_2 (and CO to a lesser extent), with no association with aldehydes.

- Ruiz et al. (2010), in a study of residential heating appliances in metropolitan Chile, found that gas heaters were associated with elevated concentrations of NO_2 and ultrafine PM, relative to homes using electric or central heating.

- Zhang et al. (2010) found higher PM concentrations resulting from cooking with gas stoves versus electric stoves, irrespective of the cooking temperature or the speed of the exhaust fan.

How effective are kitchen exhaust fans and other ventilation?

Kitchen exhaust fans have been observed to deliver widely varying results depending on fan speed, burner usage, and other factors (Mullen et al., 2012). Zhao et al. (2020) found in California that people tended to use kitchen range hoods less than 40% of the time overall, and they tended to use them more frequently when cooking frequencies were higher and when the cooking event generated noticeable PM. In Seals & Krasner (2020), written in conjunction with the Rocky Mountain Institute, Physicians for Social Responsibility, Mothers Out Front, and Sierra Club, they note that there are no uniform venting requirements for gas stoves, whether they recirculate air or vent to the outside. Delp & Singer (2012) found widely varying capture efficiencies in lab tests of exhaust hoods, depending in part on air flow and burner position, with large and open hoods covering most of the front burners being the most successful. Rim et al. (2012) found similar results regarding the performance of kitchen exhaust fans based on air flow achieved and which burners were used, finding a 30% reduction in peak concentrations of ultrafine PM at an optimized flow rate. Zhang et al. (2010) noted the efficacy of the exhaust fan can be limited when PM concentrations are very high during and just after cooking, although a high-efficiency ventilation device can remove a noticeable portion of PM emitted by gas (and electric) stoves.

Beyond kitchen exhaust fans alone, other air filtration units, air cleaners, and enhanced home ventilation also may be effective in removing IRC-generated emissions when used properly. As Adamkiewicz et al. (2011) points out from empirical evidence and modeling of IAQ, inadequate ventilation is a key determinant in indoor pollutant exposures, particularly for households of lower socioeconomic status. They found that low-income, often multifamily housing, with greater occupant density and often inadequate ventilation, tend to be more influenced by indoor sources than other populations. A Monte Carlo modeling study in China (Zhou & Zhao, 2014) suggested large improvements in indoor levels of PAHs, averaged across the simulated rural homes, if indoor particle cleaners were employed to remove indoor PAHs after they were emitted by IRC or infiltrated from outside. These indoor particle cleaners were better at removing PAH from urban and rural homes relative to kitchen exhaust fans. NCHH (2022) summarized a large study in affordable homes (rehabilitated using green building practices) which were multifamily properties in Chicago and New York City and comprised a variety of characteristics impacting IAQ including appliance type (e.g., gas versus electric; vented versus unvented), use of space heaters, and existing ventilation. They found that employing home ventilation that complies with ASHRAE Standard 62.2 can reduce peak 15-minute indoor levels of CO 25%, specifically when continuous kitchen exhaust was included. Such standard compliance with continuous kitchen exhaust also can reduce formaldehyde levels by 44%, though we are not aware of research consistently connecting IRC to indoor formaldehyde levels. Standard compliance also can reduce indoor levels of $PM_{2.5}$ by 20%, but they did not observe a benefit specifically tied to kitchen exhaust; instead, the benefits came from bathroom exhaust and likely points to indoor PM sources beyond those from cooking.

Does home weatherization impact IAQ?

Several studies examined weatherization and energy-efficient housing. In a study of many homes participating in U.S. DOE's Weatherization Assistance Program (WAP), Pigg et al. (2018) found mixed results for the impact of weatherization on indoor CO levels originating from any and all IRC sources, across many homes comprising a variety of combustion and electric appliances. These mixed results were due to confounding effects such as appliance usage differences and appliance replacements (particularly with gas ranges and furnaces), and indoor CO sources like attached garages not relevant to combustion appliances (Pigg et al., 2014) is a larger report from the Oak Ridge National Laboratory, from the same authors on the same topic). In Wilson et al. (2016), the National Center for Healthy Housing undertook a literature review centered on the impacts to the indoor environment from energy efficiency or home performance upgrades. They concluded that such upgrades, including enhanced ventilation and interventions with air cleaners and appliance replacement (as well as new green construction), generally reduced indoor pollution with varying degrees of success. For example, base energy efficiency improvements may have led to small changes in IAQ, while enhanced energy efficiency and green renovations/new construction generally led to more noticeable improvements in IAQ. The same was true specifically of enhanced ventilation (although the relative quality of the outdoor air must be considered), air cleaners, replacements of gas heating stoves with electric, and woodstove improvements.

2.2.3 Other Fossil Fuels

2.2.3.1 Summary

The sampled literature contains little information on appliances powered by fossil fuels other than natural gas [e.g., liquified petroleum gas (LPG), propane, and kerosene]. In the literature review below, we cite five such papers, which showed kerosene to have particularly large impacts on IAQ, while mixed impacts on IAQ occurred when switching from wood to fossil fuels or switching between fossil fuels.

2.2.3.2 Literature Review

Wang et al. (2020) conducted a study on a test house and found that propane-fueled stoves and particularly ovens can lead to substantially elevated levels of nitrous acid, which can be emitted directly by the appliances but also formed by reactions of combustion NO_2 on indoor surfaces. They observed that indoor levels of nitrous oxide rose from a baseline near 5 ppb to as high as over 80 ppb during intense cooking activities, especially with the oven in heavy use, and levels remain elevated for hours or days afterward due to slow desorption. A Monte Carlo modeling study in China (Zhou & Zhao, 2014) suggested large improvements in indoor levels of PAHs, averaged across the simulated rural homes, if all those homes switched from solid fuels to LPG. Gould et al. (2018) studied the effect of New York City's mandate to change boiler fuels from No. 6 oil to either Nos. 4

or 2 oils or natural gas, and they found no significant improvements in indoor levels of black carbon and $PM_{2.5}$.

Paulin et al. (2013) sampled homes in Virginia and found generally that, relative to propane, kerosene heating produces higher indoor levels of $PM_{2.5}$ (by factors of two to three: 68.9 μg/m3 and 81.8 μg/m3 for kerosene in August and December, respectively, versus 26.4 μg/m3 and 34.3 μg/m3 for propane) and NO_2 (by about 40–60%; 2.3 μg/m3 and 197.4 μg/m3 for kerosene in August and December, respectively, versus 1.6 μg/m3 and 124.0 μg/m3 for propane). They found mixed results for $PM_{2.5-10}$ (kerosene more than seven times higher in August observations [16.4 μg/m3 versus 2.2 μg/m3] but propane about 30% higher in December observations [26.1 μg/m3 versus 19.9 μg/m3]). Results were mixed when comparing levels of these pollutants between these fossil fuels and wood. Ruiz et al. (2010), in a study of residential heating appliances in metropolitan Chile, found that kerosene appliances were associated with the highest indoor levels of a suite of CAPs and HAPs.

2.2.4 Wood Fuels

2.2.4.1 Summary

In this section, we start by citing information on emission rates from RWC from approximately 21 papers or reports. Many papers (approximately 12) were not particular to the type of appliance. Relatively few papers focused on specific appliances: approximately seven papers reported on stoves, three on fireplaces, and four on heaters or boilers (some papers reported on multiple appliance types). PM emissions were a particular focus.

RWC emission factors can be widely variable, depending on appliance age and upkeep, operator behavior (including how fuel is loaded and reloaded), fuel type, etc.:

- Pellet fuels generally had lower emissions than wood (e.g., 15–45 mg PM/MJ and 52 μg PAH_8/kg from pellets, versus 35–350 mg PM/MJ and 1,000–15,000 μg PAH_8/kg from wood). Emissions can vary widely by type of pellet (e.g., from around 100 to over 3,000 mg CO/Nm^3), type of wood, and wet versus dry fuel (e.g., wet wood may produce more than twice the amount of $PM_{2.5}$ compared to dry wood).
- Emissions may vary widely by phase or type of operation (e.g., for woodstoves: 1.66–16.0 g $PM_{2.5}$/kg hot start versus 5.62–25.8 g $PM_{2.5}$/kg cold start; for masonry wood heaters: 100 mg PM_1/MJ and 300–1,360 μg VOC/m^3 during normal combustion versus 600 mg PM_1/MJ and 950–7,860 μg VOC/m^3 during smoldering).
- Emissions also may vary depending on "real-world" conditions and operator behavior versus laboratory settings or idealized behavior (e.g., 13.0 g PM/kg during "real-world" conditions versus 3 g PM/kg that commonly is used for low-emission residential wood burners). Optimized user conditions may reduce emissions by a factor of two.
- Wood fireplaces may generally have higher emissions than woodstoves, except perhaps for CO (where stoves may emit more) and NOx (where both appliances' emissions are similar).

- Old burners may emit far more than new burners (e.g., 235 g PAH/kg for old burners versus 45 g PAH/kg new burners).

We then cite information on RWC impacts on IAQ from relatively few (seven) papers or reports. These studies found that RWC influenced, sometimes substantially, the indoor levels of CO, PM, NO_2, and some HAPs like PAHs and benzene (but not formaldehyde), sometimes beyond the room containing the appliance. These impacts generally were higher for open versus closed appliances and for appliances that were older or not well maintained (newer, more efficient appliances may substantially mitigate these impacts, although sometimes not significantly).

2.2.4.2 Literature Review

What has been found regarding RWC emissions to indoors?

Studies by Shen (2013; 2021) discussed emissions from RWC. Shen et al. (2021) was a critical review particularly of studies in developing countries, but it included some developed countries, with a focus on cookstoves, heating stoves, and fireplaces. They cited two studies [Luo et al. (2021) and Shen et al. (2020)] which developed measurement methods in field conditions for wood-burning cookstoves. For wood cookstoves they found average $PM_{2.5}$ emission factors on the order of 1 g/kg (Table 5) (28±14% emitted indoors rather than through the chimney; not shown in the table), and average CO emission factors on the order of 12 g/kg (Table 6) (14±10% emitted indoors; not shown in the table), but the emission factors had a large spread in values and were much higher than those from laboratory settings. Overall, they noted that protocols for emission testing, both in laboratory settings and field studies, are not standardized, and the differences between lab and field settings in the derived emission factors are not elucidated. They note that lab studies are important in evaluating the different mechanisms and influences on pollutant emission factors. Rabaçal & Costa (2015) also observed a lack of established protocol for measurements, including units and normalization.

Table 5. From Selected Studies: Sample of Indoor Emission Rates of Particulate Matter (PM) from Residential Wood Combustion

Study	Appliance Type	Emission Rate (mean unless otherwise stated) PM	Notes
Shen et al. (2021) [from Shen et al. (2020); Luo et al. (2021)]	Wood cookstove	1.24 ± 0.95 g/kg $PM_{2.5}$	Studies in developing countries. Focus on field studies.
Shen et al. (2013)	Wood cookstove (brick)	2.1 g/kg	
Ozgen et al. (2014)	Biomass stove	200 g/GJ	Italy
	Biomass fireplace	512 g/GJ (open fireplace)	
Scott (2005)	Miscellaneous wood combustion	Median 13.0 g/kg ("real-life" conditions)	
Boman (2005)	Miscellaneous wood combustion	•15 – 45 mg/MJ (pellet fuel) •35 – 350 mg/MJ (wood fuel)	
Kasurinen et al. (2016)	Miscellaneous wood combustion	•30.2 mg PM_1/MJ (poplar pellet fuel) •26.3 mg PM_1/MJ (miscanthus sp. Fuel) •12.0 mg PM_1/MJ (straw pellet fuel) •10.9 mg PM_1/MJ (standard softwood pellet fuel)	
Ozgen et al. (2017)	Miscellaneous wood combustion	•36 mg/kg ultrafine PM (pellet fuels) •400 mg/kg ultrafine PM (wood fuels)	
Gonçalves (2011); Gonçalves et al. (2011)	Woodstove	•1.66 – 16.0 g $PM_{2.5}$/kg (hot start) •5.62 – 25.8 g $PM_{2.5}$/kg (cold start)	Portugal
	Wood fireplace	•0.84 – 21.7 g $PM_{2.5}$/kg (hot start) •8.11 – 29.0 g $PM_{2.5}$/kg (cold start)	
	Miscellaneous wood combustion	1.12 – 2.89 g PM_{10}/kg	
Jalava et al. (2010)	Masonry wood heater	•100 mg PM_1/MJ (normal combustion) •600 mg PM_1/MJ (smoldering)	
Kinsey et al. (2009)	Woodstove, Wood Fireplace	<1 – 55 g $PM_{2.5}$/kg (approx.)	Laboratory measurements
Rabaçal & Costa (2015)	Pellet boiler	<5 – <700 mg/Nm^3	Literature review
Ancelet et al. (2010)	Miscellaneous wood combustion	•16 – 17 g/kg (low burn) •7 g/kg (startup) •4 – 8 g/kg (high burn)	

Notes: PM_{10} = PM with diameter 10 micrometers or less; $PM_{2.5}$ = PM with diameter 2.5 micrometers or less; PM_1 = PM with diameter 1 micrometer or less; $PM_{0.2}$ = PM with diameter 0.2 micrometers or less; kg = kilogram; g = gram; mg = milligram; GJ = gigajoule; MJ = megajoule.

Table 6. From Selected Studies: Sample of Indoor Emission Rates of Carbon Monoxide (CO), Nitrogen Oxides (NOx), Organic Carbon (OC), and Elemental Carbon (EC) from Residential Wood Combustion

Study	Appliance Type	Emission Rate (mean unless otherwise stated)				Notes
		CO	NOx	OC	EC	
Shen et al. (2021) [from Shen et al. (2020); Luo et al. (2021)]	Wood cookstove	12.3±12.1 g/kg	NA	NA	NA	Studies in developing countries. Focus on field studies.
Shen et al. (2013)	Wood cookstove (brick)	NA	NA	0.59 g/kg	1.1 g/kg	
Ozgen et al. (2014)	Biomass stove	6,232 – 7,681 g/GJ	100 – 134 g/GJ	NA	NA	Italy
	Biomass fireplace	4,471 – 5,048 g/GJ		NA	NA	
Kasurinen et al. (2016)	Miscellaneous wood combustion	• 67.5 mg/MJ (straw pellet fuel) • 40.0 – 45.4 mg/MJ (*Miscanthus* sp., poplar, and standard softwood pellet fuels)	NA	NA	NA	
Arif et al. (2017)	Miscellaneous wood combustion	• 104 mg/Nm^3 (*Miscanthus* sp. straw fuel) • 3,410 – 3,440 mg/Nm^3 (softwood or beechwood chip fuel)	NA	NA	NA	
Kirchsteiger et al. (2021)	Wood room heater	NA	NA	• <50 mg/MJ (hot start) Up to >350 mg/MJ (cold start)	• <100 mg/MJ (hot start) Up to >200 mg/MJ (cold start)	Values are general and approximate
Rabaçal & Costa (2015)	Pellet boiler	< 50 mg/Nm^3	Approx. 150 – 500 mg/Nm^3	NA	NA	Literature review

Notes: kg = kilogram; g = gram; mg = milligram; GJ = gigajoule; MJ = megajoule; Nm^3 = normal cubic meter; NA = not addressed by the study.

Shen et al. (2013) found that emission factors of various pollutants originating from a brick cooking stove (see Table 6, and Table 7) were independent of fuel charge size, with $PM_{0.4}$ the most abundant particle size. The emissions of 28 parent PAHs (see Table 7) were dominated by naphthalene, phenanthrene, fluoranthene, and pyrene, while emissions of four oxygenated PAHs were dominated by 9-fluorenone, and emissions of six nitrated PAHs were dominated by 1- and 2-nitro-naphthalene. Emissions increased with increasing fuel moisture (generally by about a factor of two, except for EC which was relatively unchanged; not shown in Table 6). Emissions also increased with non-normal (enhanced or restricted) ventilation (generally by several factors, except for EC where normal ventilation had the highest emissions; not shown in Table 6), and PAH emissions also increased by a factor of two to four with fast-burning operation (not shown in Table 7).

Table 7. From Selected Studies: Sample of Indoor Emission Rates of Polycyclic Aromatic Hydrocarbons (PAH), Nonmethane Hydrocarbons (NMHC), Volatile Organic Compounds (VOC), and Total Suspended Particulates (TSP) from Residential Wood Combustion

Study	Appliance Type	Emission Rate (mean unless otherwise stated)				Notes
		PAH	NMHC	VOC	TSP	
Shen et al. (2013)	Wood cookstove (brick)	• 14 mg/kg (28 parent PAHs) • 0.8 mg/kg (4 oxygenated PAHs) • 5.8 mg/kg (6 nitrated PAHs)	NA	NA	NA	
Ozgen et al. (2014)	Biomass stove	NA	234 – 366 g/GJ	NA	NA	Italy
	Biomass fireplace	NA	548 – 1,011 g/GJ	NA	NA	
Arif et al. (2017)	Miscellaneous wood combustion	• 2.5 mg/kg (*Miscanthus* sp. straw fuel) • 914 mg/kg (softwood chip fuel) • 2,458 mg/kg (beechwood chip fuel)	NA	• <10 mg C/Nm^3 (*Miscanthus* sp. straw fuel) • 210 – 310 mg C/Nm^3 (softwood or beechwood chip fuel)	• 34 mg/Nm^3 (*Miscanthus* sp. straw fuel) • 114 – 149 mg/Nm^3 (softwood or beechwood chip fuel)	
Ozgen et al. (2017)	Miscellaneous wood combustion	• 52 µg PAH_8/kg (pellet fuels) • 1 – 15 mg PAH_8/kg (wood fuels)	NA	NA	NA	
Jimenez et al. (2017)	Miscellaneous wood combustion	750 – 2,100 µg/kg (particle-bound)	NA	NA	NA	
Jalava et al. (2010)	Masonry wood heater	• 1,030 ng/mg contained in $PM_{0.2}$ (normal combustion) • 2,290 ng/mg contained in $PM_{1-0.2}$ (normal combustion) • 1,450 ng/mg contained in $PM_{0.2}$ (smoldering) • 2,260 ng/mg contained in $PM_{1-0.2}$ (smoldering)	NA	NA	NA	
Stefenelli et al. (2019)	Miscellaneous wood combustion	NA	NA	• 300 – 1,360 µg/m^3 (flaming) • 950 – 7,860 µg/m^3 (smoldering)	NA	Wood combustion chamber experiments
Ancelet et al. (2010)	Miscellaneous wood combustion	• 235 g/kg (old burner) • 45 g/kg (new burner)	NA	NA	NA	
Kirchsteiger et al. (2021)	Wood room heater	• <2 mg PAH_{12}/MJ (hot start) • Up to >15 mg PAH_{12}/MJ (cold start)	NA	NA	• 50 – 200 mg/MJ (hot start) • Up to >700 mg/MJ (cold start)	Values are general and approximate

Notes: C = carbon; kg = kilogram; g = gram; mg = milligram; µg = microgram; ng = nanogram; GJ = gigajoule; MJ = megajoule; Nm^3 = normal cubic meter; m^3 = cubic meter; NA = not addressed by the study.

Ozgen et al. (2014), in a study in Italy, found that automatically fired biomass stove systems tended to produce lower emissions than manually-fed systems. Biomass fireplaces (open or closed) tended to produce lower CO emissions relative to stoves (Table 6), although higher emissions of nonmethane hydrocarbons (NMHCs; Table 7); NOx emissions were similar by these appliance types (Table 6), as were PM emissions except that open fireplaces produced substantially more PM (Table 5). The tested wood types generally did not show consistent, significant differences in emissions among the wood types, while differences in pellet quality had a greater impact on emission variability. PAH and dioxin emissions varied more by appliance type (e.g., up to 100s of mg benzo(a)pyrene /GJ in woodstoves, versus 10s of mg/GJ in fireplaces; not shown in the tables) than by fuel type (e.g., tended to lead to less than a factor of two or three variation). Pellet burners showed significantly lower emissions than other appliances (e.g., by over an order of magnitude for CO, PAHs, and NMHCs; by at least a factor of two for NOx and PM; not shown in the table).

Scott (2005) observed as PM emissions from wood-burning appliances increased, so, too, did emissions of PAHs, but with differences depending on operator behavior. The authors found a median PM emission rate during "real-life" conditions (Table 5) that was over four times the value of 3 g/kg that commonly is used for low-emission residential wood burners. McNamara et al. (2013), who measured PM and endotoxin emissions in Montana homes using older woodstoves, did not find significant correlations between emissions and usage patterns or home sizes (after adjusting for other home characteristics).

What else has been found regarding the impact of fuel type on RWC emissions?

Other than what we noted above, several other authors also examined differences in emissions from wood-burning appliances based on fuel type:

- Boman (2005), relative to wood appliances, found that pellet appliances had lower emissions of PAH and nonmethane VOC (not shown in the tables) as well as PM (Table 5), with significant variations depending on conditions (e.g., emissions during intensive combustion with high draught and extra dry and cleaved logs were generally several factors greater than with normal stove and fuel conditions; not shown in the table). Lower emissions were observed when automatically fired versus batch-wise firing.

- Kasurinen et al. (2016) observed notably higher CO emissions from some pellet types (Table 5) while higher PM_1 emissions from other pellet types (Table 5).

- Arif et al. (2017) also noticed sometimes very large differences in emissions between different straw and chip fuels (Table 6, Table 7).

- Ozgen et al. (2017) observed compositional differences in ultrafine particles between pellet fuels (mostly ash-related material) and wood fuels (mostly carbonaceous) (not shown in the tables), with more PM and PAHs released from wood (Table 5, Table 7).

- While Kinsey et al. (2009) found extremely variable $PM_{2.5}$ emissions from woodstoves and wood-burning fireplaces across different laboratory methods, appliance types, and wood species and characteristics (Table 5), perhaps it can be generalized that a substantial number of ultrafine particles were produced, and wet wood and fireplaces produced more $PM_{2.5}$ by about a factor of two relative to dry wood and stoves (not shown in the table).

- Fine et al. (2002) noted the variability in PM emissions and/or the composition of PM emissions from RWC based on the wood species (in a study about outdoor air quality, see Section 2.3).

- Jimenez et al. (2017) found that mean PM emissions varied by a factor of two, and the emissions of 12 particle-bound PAHs varied by about a factor of three (Table 7), depending on wood species, with higher proportions of fluoranthene, pyrene, benzo[a]anthracene, and chrysene relative to other compounds (not shown in the table).

- Wiinikka (2005) found that the wood species of pellets had more influence on characteristics of pellet PM emissions than did different operating and construction parameters.

- Gonçalves (2011) and Gonçalves et al. (2011), focusing on appliances and fuels common in Portugal, similarly found that emission characteristics were driven most prominently by the type of appliance (woodstove versus fireplace), operation phase (hot start versus cold start), type of biomass fuel, and the efficiency of the appliance (Table 5).

What else has been found regarding the impact of phase of operation on RWC emissions?

Other than what we noted above, several other reviewed papers discussed how appliance phase of operation can impact RWC emissions:

- Jalava et al. (2010) found substantial differences in the PM characteristics, including toxicity, from wood combustion in a masonry heater, depending on phase of operation. They generally found higher emissions particularly of larger particles (and higher emissions of PAHs and other organic content) during smoldering relative to normal combustion (see for PM_1 and for PAHs), although on an absolute basis the CO, VOC, and PM_1 emissions from normal combustion were still high, with PM_1 emissions comprising more $PM_{0.2}$ than $PM_{1–0.2}$ during normal combustion, and $PM_{1–0.2}$ making up a larger share during smoldering (not shown in the tables).

- Stefenelli et al. (2019) also noted that phase of operation is a significant driver of emission rates. They found notable differences in the emission characteristics from RWC chamber experiments depending on phase of operation and type of pollutant, with much higher levels of VOCs emitted into the chamber during smoldering (with higher contributions from furans and organic compounds with less than six carbon atoms) than during flaming (with higher contributions from aromatics) (Table 7).

- Ancelet et al. (2010) found that emissions varied by phase of operation and burner type for wood combustion, with higher PM emission rates during low burn than startup and high burn (Table 5), and higher PAH emission rates for older burners than newer burners (Table 7).

- Kirchsteiger et al. (2021), in user-habits experiments**,** found higher emissions during cold start than consecutive-batch hot starts for a wood-powered room heater (Table 6, Table 7). Optimized experiments yielded clear decreases in emissions relative to user habits, perhaps by a factor of two roughly (not shown in the tables).

- Win & Persson (2010) found higher emissions of CO and total organic compound during the start and stop phases of wood boilers and stoves, with the stove having higher accumulated emissions during startup but lower during stop. The stove had higher CO emissions during steady-state operations due to the cleaning routine (while cleaning the boiler with compressed air during the stop phase caused higher emissions from the glowing ash).

- Rabaçal & Costa (2015) was a review paper. They observed that PM emissions (and perhaps emissions of soot and VOCs) from biomass boilers and stoves likely were correlated with poor combustion conditions and more strongly correlated with ash content and composition than with appliance operating conditions, while efficient combustion generally leads to emissions of inorganic particles. The studies they reviewed showed that large ranges in emissions from pellets (Table 6), although many of the studies were using sub-optimal pellet quality.

What has been found regarding RWC impacts on IAQ?

Of the studies we reviewed, only five discussed impacts of RWC on IAQ:

- Vicente et al. (2020) found that wood-burning heating appliances created sharp increases in indoor levels of CO (but below guideline levels in Portugal) and PM_{10}, more so for open fireplaces than cast iron woodstoves. Carcinogens like PAHs and hexavalent chromium also were detected (higher PAH levels from the fireplace, higher chromium levels from the woodstove).
- Mandin et al. (2009) found that indoor wood burning influenced indoor levels of PAHs (sometimes reaching high levels), PM, NO_2, and benzene (except not for benzene from an old, closed fireplace), with no influence on formaldehyde. They were not able to observe differences between burning conditions, but when concentrations were measured in other rooms, they were of the same order of magnitude as the room containing the appliance.
- Wyss et al. (2016) found that wood-heating stoves created significant increases in indoor levels of $PM_{2.5}$ even when appliance usage was limited. A program in Norway to replace

stoves manufactured before 1997 led to $PM_{2.5}$ levels that were similar to homes not using woodstoves at all.

- However, Ward et al. (2017) found mixed results with interventions with improved woodstoves, where indoor $PM_{2.5}$ mass concentrations, and the particle number concentrations for some PM size bins, were reduced but not significantly, despite initial user training. However, CO concentrations were significantly reduced. Noonan et al. (2017) found a similar result regarding changes in indoor PM levels with improved woodstoves, and Commodore et al. (2013) did not find improvements in $PM_{2.5}$ and CO levels with improved cookstoves (although potentially affected by lack of maintenance, improper use, and lack of continuous and exclusive stove usage).
- Ward et al. (2017) and Noonan et al. (2017) found that intervention with air filtration units (which removed PM after being emitted by appliances) resulted in larger reductions in indoor PM levels than interventions with improved woodstoves, particularly when the filtration units were used optimally.
- As part of research from the Fraunhofer Institute for Wood Research, Fraunhofer (2014) noted that wood-burning stoves can have a negligible impact on IAQ if the doors are closed and well-sealed and the ventilation damper is functioning properly. However, emissions leak into the room during fuel ignition and addition, particularly with consumption of the paraffinic ignition device (relative to ignition with paper).

2.2.5 Other Fuels

As part of research from the Fraunhofer Institute for Wood Research (Germany), Fraunhofer (2014) noted that unvented ethanol fireplaces were growing in popularity in some parts of the world, but noted that measurements indicated outside of perfect conditions that CO, NO_2, ultrafine PM, and organic HAPs (including formaldehyde and benzene) can be emitted into the room, frequently at high levels exceeding non-U.S. guidelines for air quality (e.g., well over the 0.35 mg/m^3 non-U.S. IAQ guideline for NO_2, the 0.1 ppm guideline for formaldehyde, and the 1,000 ppm guideline for CO_2).

2.3. Ambient Air Pollution and Climate Change Impacts

Indoor combustion can contribute significantly to outdoor (a.k.a. ambient) air pollution. Historically, health impacts from combustion-driven events, such as London's infamous smog events, focused attention on indoor combustion's impacts. Wood is particularly of concern due to its potential to contribute to regional air quality—an issue that may be confounded by other considerations – wood is cheap, local, and long history of use in many communities - and the relatively lower GHG impacts of such fuels. On the other hand, fuels such as natural gas that have replaced fuel oil in some locations have mixed impacts. Natural gas reduces PM emissions substantially but contributes to global warming via CO_2 emissions when combusted and CH_4 via leaks and during production and transport.

This section addresses how indoor combustion contributes to outdoor air pollution, including criteria pollutants, toxic air contaminants (TACs, a.k.a. hazardous air pollutants, HAPs), greenhouse gases (GHGs), and other climate-forcing pollutants such as black carbon. In other words, this section answers the question: What are the outdoor air pollutant impacts—including concentrations, emissions, and climate implications—of IRC? Throughout, we use the terms outdoor and ambient pollution synonymously. Also, consistent with the project's scope, we examine only impacts from indoor residential combustion (IRC) and only for fuels used in the United States.

What did we review?

Of the approximately 2,000 peer-reviewed papers in our primary set, 140 papers were identified as relevant for this research area. Each of these was reviewed at the title-abstract level to prioritize for full text review. Of the 140 papers, 73 (52%) were identified as most likely relevant, and another 41 (29%) as possibly relevant. Fifty-five (39%) articles were identified as having a non-U.S. focus. This percentage represents a minimum estimation of non-U.S. articles, as it captures only those tagged as non-U.S. focus during title-abstract screening. Eighty-two (59%) were tagged as having wood as the subject, 38 (27%) as having solid fuels (including coal) as the subject, 24 (17%) as petroleum (including natural gas and oil), and 22 (16%) as having other or unknown fuels as the subject. Additional, ad-hoc references are also added to the results presented here.

We also reviewed relevant national databases. Prior to the presentation of results from the individual studies, we present a summary of EPA's National Emissions Inventory (NEI) (2017) data relevant for residential combustion. Relevant information from RECS (United States Energy Information Administration [EIA], 2015, 2020) is also included.

2.3.1 Summary

What do we know about the impacts of indoor combustion on ambient air quality and climate change?

Much, sometimes most, of the local PM concentrations are due to residential wood combustion (RWC). Woodsmoke-based PM concentrations can arise from both local combustion and long-range transport of pollutants. This is borne out in the emission inventories, observations, and modeling studies. Little comparable data on other IRC fuels are available.

For literature considered relevant to this study focused on U.S. impacts, few studies or conclusive analyses directly address the ambient air quality or climate impacts of natural gas-fired IRC. Little is known about current emission rates. The South Coast Air Quality Management District is beginning a program to test IRC cooking appliances to establish these as part of an ambient air quality management program. The literature on wood combustion is comprehensive. A moderate amount of literature on the impacts of IRC is available, generally without fuel specificity. Very little literature addresses ambient impacts of other IRC fuels relevant to the present research area.

What are the key differences in impacts between each fuel type?

When considered by fuel, residential combustion of wood dominates emissions of all CAPs, including PM except NH_3 and NOx. Wood also dominates total HAP emissions. Concentrations of wood-fired combustion are substantial, and often a majority of ambient PM, particularly in cold seasons. This is a product of both local consumption and transported pollutants and is observed in both rural and urban areas, although the relative contribution of woodsmoke tends to be largest in smaller towns. Nationally, natural gas is responsible for about two-thirds of all residential combustion emissions of NH_3 and NOx, and about 1% and 2%, respectively, of the total national inventory of those pollutants. RWC is responsible for about 96% of all residential combustion CO and VOC emissions and 98% of PM emissions. This is about 3% of the total national CO inventory, 1% of the total national VOC inventory, and about 6% of the total national $PM_{2.5}$ inventory. Oil and other fuels are primarily associated with SO_2, for which they comprise 55% of the residential combustion inventory. Large scale, multipollutant, lifecycle assessments are needed to comprehensively compare ambient impacts of IRC across fuels, but such assessments were not found in the literature.

What is the scale of these impacts?

The NOx emissions from IRC represent about 3% of the total inventory both nationally and in California. The only reviewed study exploring the ambient concentrations from IRC gas combustion predicted reductions of about 10% in ambient $PM_{2.5}$ in the California county that showed the highest potential reduction from eliminating natural gas-fired, IRC combustion, and about 0.1 µg/m3 averaged statewide, a value that excluded additional emissions from gas-fired electricity generation (Zhu et al., 2020).

Residential fuel combustion (not exclusively IRC) is responsible for 6% of the nation's GHG emissions, excluding black carbon. Although wood is sometimes claimed to be carbon neutral, it is a large source of black carbon and, thus, potentially of climate forcing. Studies have found its radiative forcing impact comparable to or larger than the other GHG pollutants other than CO_2. It also alters regional precipitation patterns and enhances ice melting in the Arctic and Himalayas. (Kirchstetter et al., 2017). We found limited information on the climate forcing emissions attributable directly to IRC in the literature. Values of between about one-quarter and about three-quarters of black carbon mass are reported here attributable to wood combustion. Switching to electricity and natural gas from fuel oils, solid fuels, and related heating fuels has been shown to reduce black carbon concentrations. We found no full-lifecycle evaluations of the climate impacts of different IRC fuels.

What are the gaps found in research on ambient air pollution and climate change impacts?

We note the following as gaps and needs identified from our research.

- 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 black carbon radiative forcing of RWC in the United States should be computed to compare the climate change impacts of RWC to those from other fuels used in residences, including electricity consumption. This is challenging for several reasons. The global warming potential of black carbon is more difficult to determine than for GHGs. The impacts of IRC-specific black carbon contribution from wood needs to be separated from other biomass burning emissions, and the U.S. GHG Inventory does not include black carbon. Also, to be complete, this analysis should consider full lifecycle impacts and needs to reflect the upstream component of petroleum fuels and how they change over time. Potential for carbon cycling with biomass combustion should also be evaluated.
- Radiocarbon dating and modeling approaches to attribute observed black carbon to different fuels could present potential opportunities. This approach could leverage existing black carbon monitoring networks for better coverage across the country. Studies with temporal resolution would be of interest. Attribution of fossil black carbon to IRC specifically, however, would be challenging.
- 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 (Zhao et al., 2019) 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 O3 impacts from NOx reductions must be considered, and the potential for enhanced spatially or seasonally varying impacts. More comprehensive, fuel-comparing evaluations are needed.
- 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.

- Air quality and climate benefits of emerging fuel alternatives, including the different "colors" of H_2 (e.g., "green hydrogen," which is produced with renewables, and "blue hydrogen," which is produced using natural gas, steam reforming, and carbon capture and storage), and renewable natural gas (RNG), should be further explored. Such an exploration would need comprehensive, lifecycle assessments for the upstream components and the evaluation of combustion byproducts targeted on these fuels as used in residences. Preferably, this could be compared to a lifecycle assessment for residential electricity use. The small amount of literature we found on these fuels indicates they may not be beneficial in reducing either traditional or climate-forcing pollutants. More comprehensive, multipollutant evaluations are needed.
- Fuel mixes have and will continue to change. Although IRC is a relatively small contributor to national total emissions currently, as emissions from other sectors are reduced IRC could become more significant. Also, policies affecting appliance purchase/install decisions will have impacts for years to come. We found no studies that forecast future IRC fuel mixes or impacts.

2.3.2 National Overview of Ambient Air Pollution and Climate Change Impacts from Residential Combustion

A comprehensive overview of air pollutant emissions from all 50 states, the District of Columbia, and Puerto Rico is available from EPA. The National Emissions Inventory (NEI) (EPA, (2017) is released every three years based on data provided by State, Local and Tribal agencies. The most recent NEI data is the 2017 version released in April 2020. It does not include GHG emissions, which are reported separately, but does provide sectoral emissions across the United States, including emissions from residential combustion tracked by four fuel categories: natural gas, oil, wood, and other.

Table 8 summarizes the national, total emissions for these four fuel categories for the CAPs CO, NOx, PM_{10}, $PM_{2.5}$, and SO_2, NH_3, VOCs, and sum of all HAPs. Nationally, natural gas is responsible for about two-thirds of all residential combustion emissions of NH_3 and NOx, and about 1% and 2%, respectively, of the total national inventory of those pollutants. Residential wood combustion is responsible for about 96% of all residential combustion CO and VOC emissions and 98% of PM emissions. This is about 3% of the total, national CO inventory, 1% of the total VOC, and about 6% of the total, national $PM_{2.5}$ inventory. Oil and other fuels are primarily associated with SO_2, for which they comprise 55% of the residential combustion inventory (and a negligible portion of the total, national SO_2 emission inventory).

Table 8. National Total Emissions of Criteria (in tons) and Total Hazardous Air Pollutants (in lbs) from Residential Combustion and Overall National Total

Residential Fuel Source	Ammonia	Carbon Monoxide	Nitrogen Oxides	PM_{10} Primary[a]	$PM_{2.5}$ Primary[a]	Sulfur Dioxide	Volatile Organic Compounds	Total HAP
Natural Gas	33,772	89,251	205,415	4,205	4,044	1,370	12,116	1,535,520
Oil	1,553	8,898	33,248	3,827	3,344	11,529	1,055	218,128
Wood	16,876	2,398,362	39,272	338,916	337,310	8,695	333,174	137,268,986
Other	92	8,775	31,323	182	161	711	1,187	78,594
Total, Residential	52,293	2,505,287	309,258	347,130	344,858	22,305	347,531	139,101,229
Total, All Categories [b]	4,319,948	70,794,464	11,785,882	17,062,926	5,706,842	2,714,860	43,073,060	N/A

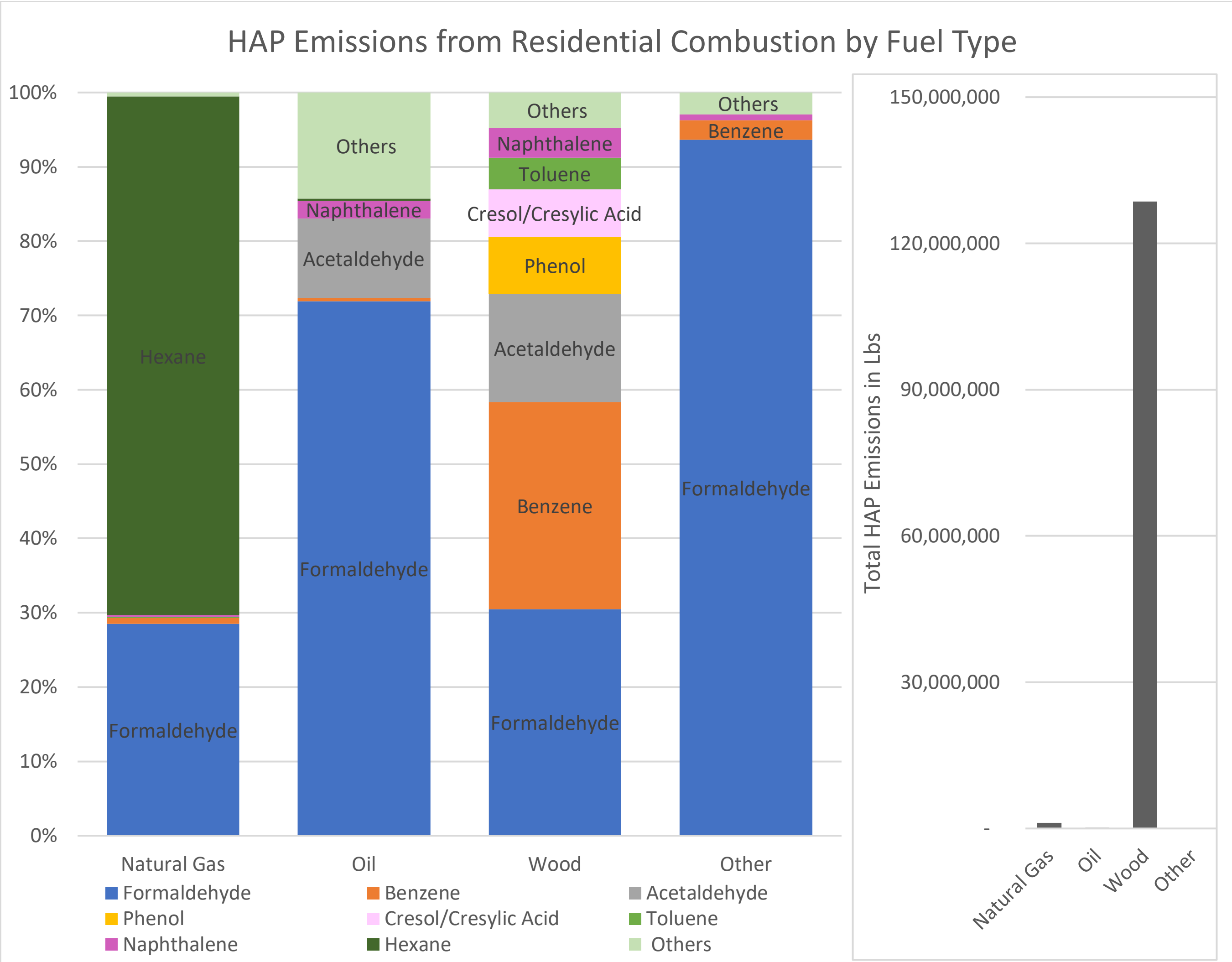
Data source: EPA (2017)

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

[b] Value is the total national inventory of all categories reported in the NEI.

Figure 8 shows the relative contribution of each reported HAP to demonstrate the relative importance by fuel type. This figure includes an inset showing the same, but in absolute units (pounds). Figure 8 clearly demonstrates the national-level contribution of HAP emissions from IRC by fuel type. For natural gas, the main HAP emissions are hexane and formaldehyde. Formaldehyde and acetaldehyde are those from oil. The biggest portion of HAP emissions from wood are formaldehyde, benzene, and acetaldehyde. These values are not weighted by their toxicity.

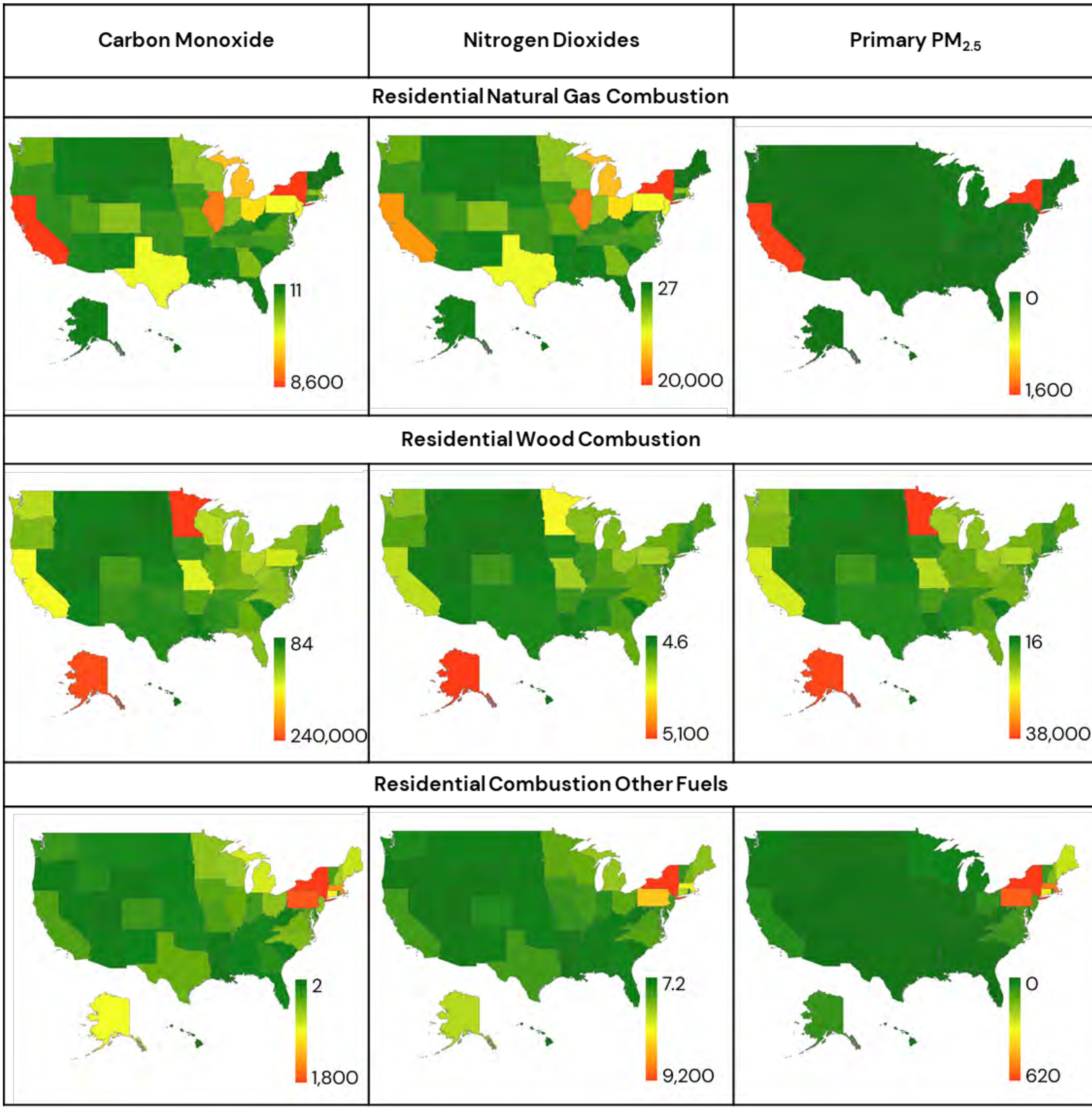
Figure 8. Relative Share of HAP Emissions from Residential Combustion by Fuel Type, 2017



Data source: EPA (2017)

Figure 9 shows national maps of state-level IRC emissions for select CAPs. The top row shows emissions for all IRC together. The second and third show results by fuel type, with wood shown in the second row and all other fuels in the third.

Figure 9. National Maps of State-level Residential Emissions for Select CAPs, 2017 (tons per year)



Data source: EPA (2017)

Although the NEI does not calculate GHG emissions, the most comprehensive national evaluation is from the EPA GHG Inventory (2022c). In 2020, residential emissions nationwide of the six GHGs comprised 6% of the national inventory. Of the total 362 million metric tons of CO_2e from fossil fuel combustion 89% (321 MMT CO_2e) is from households. (The remaining 11% is from release of fluorinated gases by households.)

We found no peer-reviewed studies directly calculating IRC CO_2 emissions by fuel, although this may easily be computed. Although the NEI does not report CO_2 or most other GHG emissions, these can be calculated from energy consumption. The RECS (2015, 2020) results for national, total residential consumption by fuel type are available from EIA and are summarized for 2021 RECS report for residential, fossil fuel, primary energy consumption values, as shown by Table 9. One approach for estimating CO_2 emissions would be to couple residential natural gas consumption from RECS (2015, 2020) with emission factors from EPA's Compilation of Air Pollutant Emissions Factors AP-42 (2022a) to determine mass of emitted CO_2 from residential combustion. AP-42, Section 1.4, provides an emission factor of 120,000 lbs. CO_2 per million standard cubic feet of natural gas. For petroleum, AP-42 Table 1.3-12 of provides CO_2 emission factors.

Table 9. Primary Consumption, Residential, 2021 Total for Fossil Fuels. (Trillions of BTUs)

Natural Gas	Petroleum
4,824	969

Data source: RECS. https://www.eia.gov/totalenergy/data/monthly/pdf/sec2_5.pdf

This is also borne out by the NEI (United States Environmental Protection Agency [EPA], 2017), which does include black carbon emissions. Table 10 shows elemental carbon emissions from the NEI and energy consumption for comparable categories from RECS, both for 2017. The fourth column ratios these to show an equivalent average emission rate, in grams per million BTU, demonstrating the relative difference in black carbon emissions among fuels as consumed. This is used for comparison purposes only given the difference in fuel categories between the studies.

Table 10. 2017 National Black Carbon Emissions, 2017, in Tons, and Primary Energy Consumption, Trillions of BTU.

Sector	Elemental Carbon Portion of $PM_{2.5}$-PRI (tons)	Primary Energy Consumption (Trillion BTU)	Calculated Equivalent Average Emission Rate (g/MBTU)
Residential Fuel Combustion: Natural Gas	257.4	4,563	0.05
Residential Fuel Combustion: Oil	387.9	871[a]	0.40
Residential Fuel Combustion: Wood	18821.0	430[b]	40.

Data source: NEI (2017); RECS (United States Energy Information Administration [EIA], 2015, 2020)

[a] Value corresponds to "petroleum" category in RECS

[b] Value corresponds to "biomass" category in RECS.

2.3.3 Natural Gas

2.3.3.1 Summary

Our research found few studies or conclusive analyses directly addressing the ambient air quality or climate impacts of IRC of natural gas. Of those identified, one study looked at leaks of unburned natural gas from stoves and found approximately 1% of the fuel is released as unburned methane equating to an additional 2.4 million metric tons CO_2e released. Reflecting this uncertainty in appliance emission rates, the South Coast Air Quality Management District (SCAQMD) is developing a testing program for cooking appliances and exploring technologies for miscellaneous residential combustion appliances. In addition, SCAQMD is proposing measures to reduce or eliminate IRC from natural gas combustion in water and space heating. When comparing the difference in emissions of UFP between petroleum and renewable natural gas-fueled IRC appliances, one study noted that use of biomethane can match, or cause higher, emissions depending on fuel properties, particularly fuel sulfur. Another study found UFP emissions from IRC to be negligible due to their volatility.

A modeling study found residential gas combustion to be the largest source of relative disparities to people of color from ambient exposures, although it did not report the underlying concentrations. Another modeling study for a scenario that eliminated IRC natural gas combustion in California found the potential to reduce total ambient $PM_{2.5}$ in the state by an average of 0.11 $\mu g/m^3$. In the county showing the greatest reductions, PM concentrations would be reduced about 10%, although these effects excluded any additional emissions from increased electricity generation.

CH_4 is a powerful greenhouse gas. Methane leaks across the gas supply and distribution chain may be significant contributors to climate change (Buonocore & Salimifard, 2021), although attributing them only to use in IRC is challenging. We found no studies on the full lifecycle assessment of natural gas specifically for IRC. Related, RNG has been considered as a lower carbon alternative to fossil natural gas. Although not specifically related to IRC, Grubert (2020) found that in practice RNG would produce negative climate benefits.

2.3.3.2 Literature Review

What are the reported GHG impacts?

Lebel et al. (2022) estimated unburned methane gas releases from natural gas-fueled stoves. It studied 53 U.S. homes. It concluded that stoves emit 0.8-1.3% of the gas they use as unburned methane and that total U.S. stove emissions are 28.1 Gg CH_4 per year, more than the total EPA GHG Inventory reported value of methane emissions for all residential stationary combustion from natural gas of 24 Gg CH_4 per year. Combining the total methane and combustion-based carbon dioxide emissions from stoves and using a 20-year global warming potential, they calculated that methane emissions add an extra one-third of CO_2e emissions to combustion-based CO_2 emissions from stove natural gas use, or an additional 2.4 MMT CO_2e from methane emissions due to cooking. More than three-quarters of methane emissions were measured during steady-state-off. They found methane emissions from cooktops to be comparable to the CO_2 impact of approximately 500,000 cars. Lebel et al. (2022) was the only peer reviewed study we identified that directly addresses natural gas appliance contributions to ambient air quality or climate change.

What are the reported PM impacts?

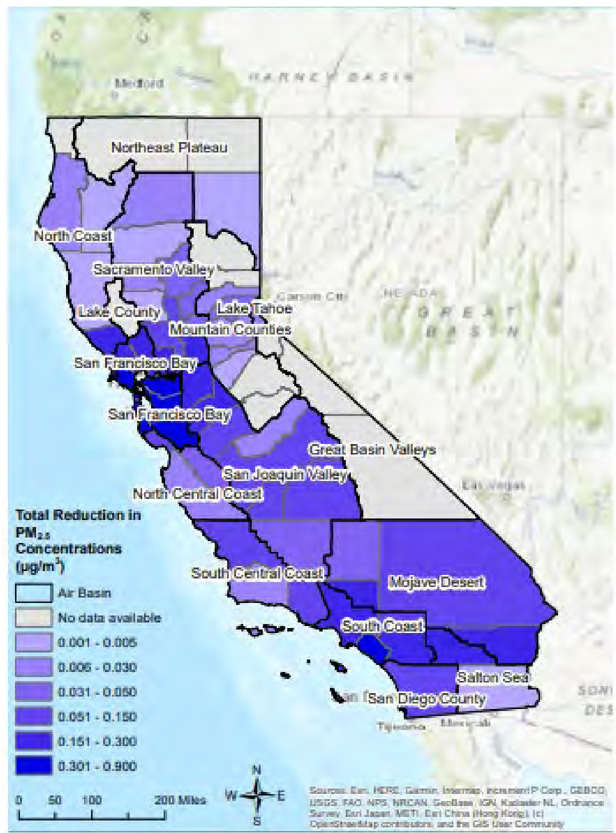
Xue et al. (2018) focused on measuring UFP (diameter < 0.1 mm) emissions from the combustion of biomethane and biogas (aka, RNG) compared to petroleum natural gas. RNG from five different sources (two food waste digesters, two dairy waste digesters, and a landfill) was combusted and exhaust measured in several appliances, including a cooking stove and a water heater. Tests were baselined against pipeline natural gas. The primary result is that biogas can increase emissions depending on fuel properties, although even the highest emitting engines on biomethane emit 4-5 orders of magnitude less than the emission from biomass burning.

Tessum et al. (2021) performed a modeling study to quantify the $PM_{2.5}$ exposure caused by all domestic anthropogenic source categories, including residential gas combustion, for year 2014. The focus of the paper is on the potential for systemic $PM_{2.5}$ exposure disparity experienced by people of color. Results are presented by demographic and source category. The information presented is limited as it is only a *Science* letter. The paper shows that nearly all major emission categories—consistently across states, urban and rural areas, income levels, and exposure levels—contribute to the systemic $PM_{2.5}$ exposure disparity experienced by people of color. For year 2014, this study found total population average $PM_{2.5}$ exposure from all domestic anthropogenic sources of 6.5 $\mu g/m^3$ in the contiguous United States, but higher exposure concentrations for POC, Blacks, Hispanics, and Asians (7.4, 7.9, 7.2, and 7.7 $\mu g/m^3$, respectively, and lower than average for Whites (5.9 $\mu g/m^3$). Residential gas combustion is the largest source of relative disparities for all four groups. Population exposure $PM_{2.5}$ concentrations attributable to residential gas combustion underlying the results are not reported.

Yu et al. (2018) focused on the San Francisco Bay and South Coast Areas in California. It looked at the main generation of UFP PNC and mass ($PM_{0.1}$), including residential natural gas combustion, traffic, woodburning, and secondary aerosol. Measurements found that UFP emitted from IRC of natural gas were semi-volatile (when diluted by a factor of 25 in clean air) while particles emitted from industrial sources of natural gas combustion did not evaporate under the same conditions. It then used this conclusion to justify setting to zero near-field emissions of UFP from IRC of natural gas and only tracking other natural gas combustion sources. In other words, this study explicitly assumed UFP concentrations from IRC of natural gas to be negligible due to their volatility. The model tracked emissions from on- and off-road gasoline vehicles, on- and off-road diesel vehicles, food cooking, biomass burning, non-residential natural gas, and all other sources.

UFP emissions from the home appliances generally had a unimodal size distribution with all fuel types, with a nucleation mode smaller than 10 nm,. Sulfur content from four facilities ranged dramatically (2.8, 2.4, and 0.8 ppm compared to pipeline CNG of 0.5 ppm. PN and mass rates varied accordingly. PN and mass measured in the cooking stove exhaust fueled with RNG were 1.54 ± 0.15 × 105 #/cm^3 and 0.17 ± 0.05 µg/m^3 (fuel consumption rate = ~9 L/min, DF = 31–37). These concentrations are 83 and 18 times higher than PN and PM measured using CNG. Results generally correspond to the sulfur content of the fuel and suggest that sulfur pretreatment should be used for RNG. Raw UFP concentration from domestic gas cooking measured using the cooking stove and water heater (103 to 105 #/cm^3) were consistent with previous studies. UFP emission rates measured from the combustion of petroleum natural gas in the current study ranged from 1.0 to 8.1 × 10^{12} #/kg fuel.

Figure 10. Potential Reduction in Ambient $PM_{2.5}$ Concentrations in California from Elimination of Gas Appliances, by County in 2018.



Source: Zhu et al. (2020).

What are the reported NOx impacts?

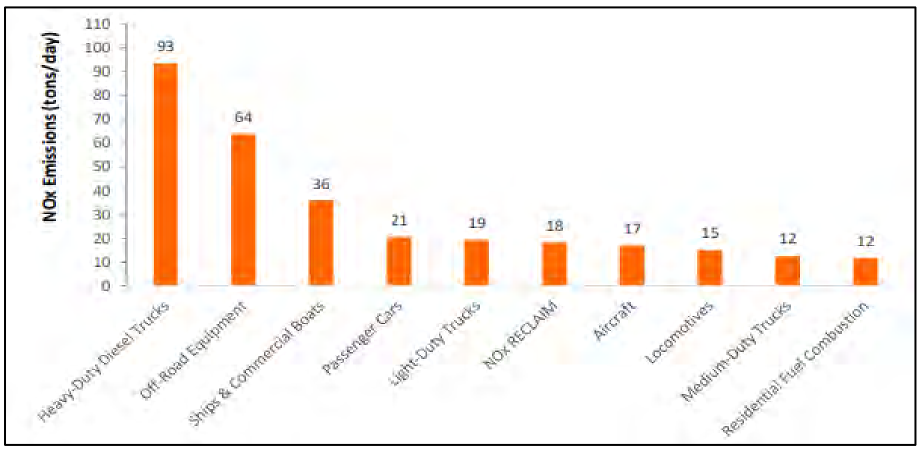
Zhu et al. (2020) includes a literature review and modeling exercise to calculate the impact on ambient air quality in California from natural gas-fueled IRC from various gas-fueled appliances. It found approximately 12,000 tons of CO and 15,900 tons of NOx to be emitted from gas-fueled IRC in California in 2018, in agreement with state inventory estimates. It found that natural gas-fueled IRC accounts for approximately 3% of total NOx emissions in California (roughly consistent with the national totals from NEI (2017)). It notes that more than 90% of California households use gas for at least one purpose, and 70% of for cooking, with gas water and home heating appliances are responsible for the bulk of outdoor air pollution from gas appliances. Water heaters are the largest contributor to gas-fueled IRC CO emissions (36.5%) while heating appliances are the largest gas-fueled IRC NOx emitters (44%) in California in 2018. Zhu et al. (2020) also modeled reduction potential for total (primary plus secondary $PM_{2.5}$, with secondary based on reduced nitrate component) $PM_{2.5}$ concentrations from statewide replacement of gas appliances. Statewide, they found an average reduction in ambient

$PM_{2.5}$ concentration of 0.11 µg/m^3, with reductions up to 0.85 µg/m^3 (San Francisco County).[12] This excludes any additional gas-fueled electricity generation emissions.

The South Coast Air Quality Management District (SCAQMD) recently released its 2022 Air Quality Management Plan (AQMP) (Baranizadeh et al., 2022) focused on attaining the 2015 8-hour ozone standard. One area targeted by the aggressive new regulations and incentives is residential NOx emissions. These "building measures," are intended to align with California's goals for statewide zero GHG emissions from residential and commercial buildings. The 2022 AQMP includes four proposed ozone measures to reduce or eliminate gas combustion in households. The first two measures would require zero emission or low-NOx water heating and space heating units in both new and existing residences. The third measure focuses on replacing gas burners with electric cooking devices, induction cooktops, or low NOx gas burner technologies. The fourth measure targets a mix of indoor and outdoor residential natural gas and LPG fired equipment, such as swimming pool heaters, laundry dryers, and barbecue grills.

Combined, SCAQMD predicts these measures could reduce NOx emissions by 2.4 tons per day in 10 years (2032) and 6.43 tons per day in 15 years (2037). Figure 11 shows the current (2018) NOx emissions inventory for the region by sector, which demonstrates the relative contribution of the residential sector.

Figure 11. Top Ten Categories for NOx Emissions in California's South Coast Air Basin in 2018.



Source: SCAQMD 2022 (Baranizadeh et al., 2022).

2.3.4 Other Fossil Fuels

2.3.4.1 Summary

Our review examined only one study focused on other fossil fuels. It tracked changes in indoor and outdoor concentrations after a mandatory fuel switch from heavy fuel oil in New York City. It showed significant reductions in $PM_{2.5}$ near apartments that switched fuels but overall modest changes in regional $PM_{2.5}$ and black carbon.

2.3.4.2 Literature Review

Gould et al. (2018) studied domestic heating appliances during a phase-out of No. 6 fuel oil to No. 4 or No. 2 fuel oils or natural gas in New York City. This study examined changes in indoor and near-residence, ambient air pollution patterns related to heating fuel conversion by fuel type. It

[12] For comparison, the Bay Area Air Quality Management District (BAAQMD) reports the 3-year $PM_{2.5}$ annual design value for the 2017-2019 period excluding wildfire influences for San Francisco County is 8.4 µg/m^3. Bay Area Air Quality Management District [BAAQMD] (2020).

compared results to regional, observed $PM_{2.5}$ and black carbon concentrations reported by the New York City Community Air Survey (NYCCAS) over the same time-period. NYCCAS reported significant wintertime declines for SO_2 and some reductions for $PM_{2.5}$ and black carbon. This study found comparable near-field changes. While indoor $PM_{2.5}$ stayed the same before and after in follow-up at 12.8µg/m^3, outdoor air pollution fell from 8.96 to 8.08 µg/m3, but when considering only apartments switching to No. 2 (diesel) or natural gas, outdoor air concentrations were observed to reduce significantly after fuel conversion. Ambient black carbon levels also fell, and more so in buildings converting to lighter fuels including natural gas, but the difference between the changes in the two groups was not statistically significant. Although the study reported results of fuel switching, all involving petroleum fuels, results were not presented in a way that tracked individual fuels.

2.3.5 Wood Fuels

2.3.5.1 Summary

Ambient air quality impacts from wood combustion are thoroughly documented. Many studies are European, but several are U.S.-based. We have briefly summarized some of the most relevant here. One previous literature review study was identified and documented here. Several studies refer to “solid fuels.” Of those, we excluded any that focus on coal.

RWC is a major, often the dominant, contributor to ambient $PM_{2.5}$ and related pollutants. A West Coast study documented RWC contributions range from 11% to 93% (highest in small towns), 7% to 31% annual averages in the Seattle area, 6-month average winter contributions of 40% in Fairbanks Alaska, 74% to winter $PM_{2.5}$ in a small British Columbian town, and 56% and 77% in western Montana. In European cities the annual average contribution can be 2-30%, and regionally transported smoke may be 10 times the contributor of local emissions. In northern Sweden 31% to 83% of winter PM_1 and 40-76% of black carbon mass is RWC, where local road traffic contribution is 17%. RWC chemistry is well studied. RWC is also a leading contributor, possibly the dominant source, of PAHs including benzo[alpha]pyrene (BaP), organic aerosols, and potentially UFP. This is documented in rural areas, in U.S. cities, and in continental scale studies. One study showed that wood combustion leads to photochemical pollutant formation (e.g., ozone), but that pellet fuel exhaust may be less reactive than solid wood. The spatial distribution and impacts are also well documented. A changeout program in Montana showed the RWC contribution to remain unchanged at about 80% but reduced the overall $PM_{2.5}$ burden.

We generally did not search for carbon cycling with biomass fuels specifically related to IRC. (Buonocore & Salimifard, 2021) Biofuels are often said to have no net CO_2 emissions, although this claim is controversial. Black carbon emissions from wood and other biomass burning, however, has been well studied. Although many papers relate black carbon and optical properties to biomass or solid fuel burning generally, few are linked specifically to IRC. For example, Viana et al. (2015) presents measurements of black carbon from wood combustion in Europe, although not directly applicable to the United States and only for wood. Another example is Yang (2009), which measured properties of air masses influenced by IRC but focused on coal combustion in Northern

China, which is not applicable here. We did not review the broad literature on black carbon emissions and climate forcing from biomass burning, generally.

2.3.5.2 Literature Review

How does the fuel or technology affect ambient air pollution?

Ward et al. (2010) studied fine particulate matter source apportionment following a large woodstove changeout program to improve air quality in Libby, Montana. As a part of the study, 1,200 old woodstoves were replaced with cleaner burning models, which resulted in a 20% reduction in ambient $PM_{2.5}$ and 28% reduction in woodsmoke-related $PM_{2.5}$. Pre-changeout, approximately 80% of ambient $PM_{2.5}$ was due to residential wood combustion during the winter months. Post-changeout, $PM_{2.5}$ still accounted for 81%, however, overall $PM_{2.5}$ mass was reduced significantly. When comparing the $PM_{2.5}$ mass results of 2003–2004 with post-changeout concentrations of 2007–2008 using FRM sampler measurements showed a 20% reduction (28% when comparing speciated sampler values). Several other studies are based on the Libby intervention and discussed elsewhere in this review. (e.g., Noonan et al. (2011).)

Reyes et al. (2019) compares the emissions from a pellet and woodstove with the help of a photochemical chamber. The study found that residential wood combustion emits a substantial amount of particles and gases, including photochemically active pollutants. This study reports that gases emitted by pellets show a photochemical activity rate significantly slower than that of the gases emitted by firewood.

Gon & Bergström (2015) presents an emission inventory for residential wood combustion accounting for semi volatile components of the emissions. Including these corrections in inventory estimates increases RWC emissions by a factor of 2–3 (with substantial inter-country variation) and leads to improved agreement with observations. The study also summarizes PM_{10} emission factors under two testing approaches (solid particle (SP) and dilution tunnel (DT)). RWC emission rates are summarized in Table 11.

Table 11. Residential Wood Combustion Emission Rates

Appliance	g/GJ (SP)	g/GJ (DT)
Fireplace	260	900
Traditional Heating Stove	150	800
Medium boiler automatic	40	45
Medium boiler manual	70	80
Single house boiler automatic	30	60
Single house boiler manual	180	1000

Source: Gon & Bergström (2015)

What documented RWC impacts did we find in the U.S.?

We found many. In addition to the national values documented in Section 2.3.2. For example, Kotchenruther (2016) is a source apportionment study of $PM_{2.5}$ for 19 Northwest U.S. monitoring sites. Residential wood combustion contributions to $PM_{2.5}$ spanned a wide range. It identified sources including aged wood smoke and secondary organic carbon, primary wood smoke, and residential fuel oil combustion.

Wood smoke was identified at every site, with both primary (fresh) and aged (chemically reacted) wood smoke identified at most sites. Wood smoke contributions to $PM_{2.5}$ were averaged for the two winter months of December and January, the months when wood smoke in the Northwest U.S. is mainly from residential wood combustion. The total contribution of residential wood combustion, that from primary plus aged smoke, ranged from 11.4% to 92.7% of average December and January $PM_{2.5}$. Results show a wide range of total wood smoke percent contributions to average winter $PM_{2.5}$, from 11.4% in Bakersfield, CA to 92.7% in Lakeview, OR. The highest winter wood smoke percent contributions occur in small towns where, in addition to residential wood combustion, there are fewer potential sources of primary $PM_{2.5}$. The study also cites several papers on residential wood combustion, $PM_{2.5}$, and health impacts, including annual average wood smoke impacts at 5 sites in the Seattle area ranging from 7% to 31% of total $PM_{2.5}$ (generally lower from annual averaging), 6-month average winter wood smoke contributions of 40% to total $PM_{2.5}$ in Fairbanks Alaska, 74% to winter $PM_{2.5}$ in the small community of Golden, British Columbia, Canada, and between 56% and 77% of total $PM_{2.5}$ in five western Montana valley communities.

Figure 12. Wintertime Woodsmoke Contribution in the Pacific Northwest.

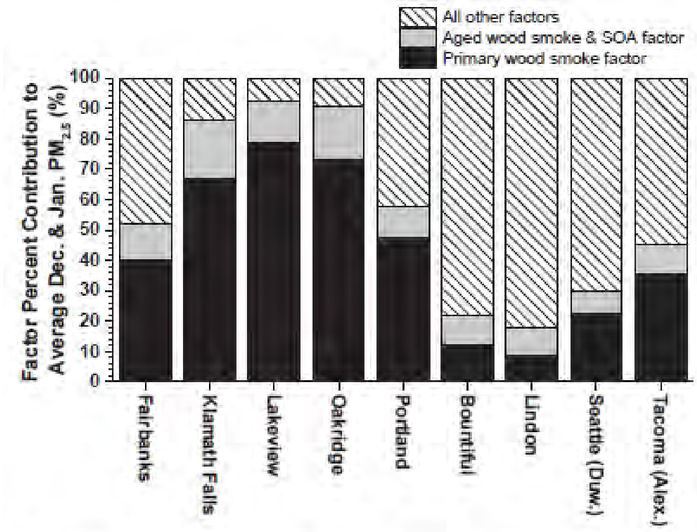


Fig. 5. Factor percent contribution to average December and January $PM_{2.5}$ for sites where two wood smoke factors were identified.

Source: Kotchenruther (2016)

Allen et al. (2011) performed an intensive characterization of ambient PM from residential wood combustion in northern New York State during winter 2008–2009 in an area where the 2005 NEI shows RWC to be the largest source of $PM_{2.5}$. Woodsmoke was the only significant contributor to elevated night-time valley PM concentrations during mobile run nights; short-term (3 minute) PM concentrations frequently exceeded 100 µg/m3. Data from fixed sites indicated that woodsmoke levels peaked near midnight, with a secondary peak around 7 AM and a mid-day minimum. These patterns are consistent with RWC use and diurnal patterns of atmospheric dispersion.

Zhang (2015) applied in a modified Community Multi-scale Air Quality (CMAQ) model (v5.0.1) to simulate ambient concentrations of PAHs and quantify the contributions of different emission sources to the predicted concentrations. The study found residential wood combustion to be the largest source of 16-PAH in three U.S. cities New York, Los Angeles and Houston. It accounted for 54% of PAH in New York, 34%-25% in Los Angeles and Houston. Higher contributions in New York are expected because of colder winters. The absolute contributions of residential wood combustion to 16-PAH in January were 0.148 µg/m^3, 0.0183 µg/m^3, and 0.0352 µg/m^3 for New York, Los Angeles, and

Houston, respectively, showing how important wintertime wood combustion is to HAP concentrations even in major urban areas.

Fine et al. (2002) is a U.S. continental-scale evaluation of woodsmoke emissions and their chemical composition. Wood smoke in the atmosphere often accounts for 20–30% of the ambient fine particle concentrations. In communities where wood is burned for home heating, wood smoke can at times contribute the majority of the atmospheric fine-particle burden. Fine-particle emissions from residential wood combustion are most concentrated in the Northeast, where population density is generally higher and cooler weather increases the need for home heating. In western states that have lower population densities and/or warmer climates, the emissions density per unit land area is considerably less. On a per capita basis, fine-particle residential wood combustion emissions are highest in New England and trend lower toward the west. 34% of the total nonfugitive dust $PM_{2.5}$ emissions in the United States for year 1995 came from biomass combustion sources, with 36% of that figure coming from residential wood combustion. This study derives regional average residential wood smoke composite emission factors including for fireplace and woodstove combustion. It notes the influence of different wood combustion appliances and emissions control equipment, which can lead to very different emission characteristics even when the same woods are burned. It also cites examples for a 3-day period in Fresno, California, in 1995, where over 50% of the ambient fine PM concentrations were due to wood combustion and that the 1982 annual average in southern California had up to 10% of the ambient fine PM from wood smoke.

Corsini et al. (2019) is a review of articles which look at the UFP emitted by biomass combustion and its impact on human health. In some polluted California cities, wood burning may be the largest contributor (32–47%) to OC, including the Fresno site in winter, due to the widespread use of wood for domestic heating. In Los Angeles wood became significant only during winter holidays due to the use of fireplaces. At all the investigated sites, wood burning gave only a small contribution to EC (1–3%). The role of wood combustion for domestic heating has increased winter-to-summer concentration ratios for typical tracers of wood combustion, such as levoglucosan and its isomers, K+, and benzo(a)pyrene. Benzo(b)fluoranthene and benzo(a)pyrene. Their concentrations were about 11- and 5-times higher during winter than during summer, respectively; both emitted in abundance by small scale appliances burning wood and pellets.

What documented RWC impacts did we find in non-U.S. countries that are also relevant to the U.S.?

Wood use, particularly in Europe, is well studied. For example, Viana et al. (2015) is a technical report focused on RWC in Europe and the impacts on air pollution and GHGs. Benzo[alpha]pyrene (BaP) emissions from the residential combustion sector contributes 55-95% to the total BaP emissions. BaP monitoring data suggests a strong contribution from heating emissions. With residential combustion being the dominant source of BaP, emissions take place at a low height and therefore have a much larger impact on the population exposure than, for example, industrial sources with taller stacks. In both cases (PM_{10} and $PM_{2.5}$), contributions are in general higher in rural and regional background areas than in urban or suburban ones. This implies that regional-scale wood burning contributions to atmospheric aerosols constitutes an additional source of PM in urban areas, where the local contributions from the residential sector to the PM load is superimposed over the regionally transported aerosols from the same source.

This study also includes a non-exhaustive literature review. It showed that in the case of $PM_{2.5}$, residential combustion (focused on wood) accounts for 2% to almost 30% on an annual mean, ranging between 20-30% during the winter heating season. This review focused on wood combustion generally excluded contributions from combustion of other fuels (e.g., coal, liquid or gaseous fuels). Overall, several of the studies carried out in urban areas (e.g., Vienna, Berlin, Zurich) report that the PM_{10} or $PM_{2.5}$ from residential combustion sources originates mainly from regional-scale transport, and that only a minor proportion is emitted locally.

There are several reasons for the relatively high emissions of toxic pollutants from residential wood burning, including the use of nonregulated stoves, the inadequate maintenance of stoves installed in homes, and/or the use of non-standard fuels (like treated, painted or not sufficiently dried wood) which hinder an efficient combustion. The study notes that modern woodstoves with a high efficiency (>75%) and low emissions are becoming available.

The study concluded that, while wood is a renewable fuel and quasi neutral with regard to GHG emissions, residential combustion of wood has a substantial impact on both local and regional-scale air quality (quantified for PM_{10}, $PM_{2.5}$, black carbon, EC and OC).

Krecl et al. (2008) looked at the contribution of RWC and other sources to hourly winter aerosol in Northern Sweden determined by PMF. The study found that local RWC accounted for 36 to 82% of PM_{10} and 31 to 83% of PM_1, significantly higher compared to local traffic which was 18% and 17% for PM_{10} and PM_1, respectively. It found the RWC range for M_{LAC} of 40-76% in the winter season.

Bari et al. (2010) investigates the particle-phase PAH composition of ambient samples in order to assess the influence of wood combustion on air quality in residential areas in Stuttgart, Germany. PM_{10} samples were collected during two winter seasons in rural residential areas. There were significant correlations between total PAHs (R^2=0.73) and BaP (R^2=0.76) and levoglocosan, suggesting that small-scale wood combustion is the dominant source of these HAPs. High correlation between total PAHs and syringaldehyde (R^2=0.77) and acetosyringone (R^2=0.85) indicates that the influence of hardwood combustion emissions is significant, and that small-scale wood-fired domestic heating may contribute significant concentrations to ambient PAHs in the residential site.

Ancelet et al. (2014) used positive matrix factorization on elemental data from 2008-2009 to identify sources of PM_{10} in Nelson, New Zealand. PM_{10} concentrations peaked during winter when domestic wood combustion for home heating is common. Carbonaceous species were found to dominate PM_{10} mass concentrations. Biomass burning accounted for 35% of PM_{10} mass overall but up to 70% during peak PM_{10} pollution days. Concentrations varied by day of week (weekend/weekday) and month.

Krecl et al. (2008) estimated the contribution of RWC to the total atmospheric aerosol loading using PMF for hourly mean particle number size distributions measured in a residential area in Lycksele, Sweden, during winter 2005/2006. The results reveal RWC is an important source of atmospheric particles in the size range 25–606nm (44–57%), PM_{10} (36–82%), PM_1 (31–83%), and M_{LAC} (40–76%) mass concentrations in the winter season. The contribution from RWC is especially large on weekends between 18:00 LT and midnight whereas local traffic emissions show similar contributions every day. It found that 31-83% of PM_1 was from local RWC, 0-52% was from long range transport of pollutants, 17% from local traffic. It characterized the climate impact in terms of MLAC (mass light absorbing carbon), with 40-76% attributed to local RWC, compared to 24% from local traffic and 0-36 from LRT. Although this study is non-U.S., the fuel mix (40% residential heating fueled by electricity, 21% combined firewood and electricity, and 11% exclusively biofuel combustion), meteorology, and climate comparable to some U.S. areas.

2.3.6 Other Fuels and Mixed Fuels

2.3.6.1 Summary

A substantial body of literature considers ambient air quality impacts of IRC generally, without reporting results by fuel type. A systematic review of studies found that IRC contributes 20% of population-weighted, urban, $PM_{2.5}$ concentrations globally and 12% in the United States. Modeling studies relate air quality (and health impacts) to IRC and note that wood is a leading contributor. Another noted the amount of IRC emissions that could be saved by increased use of residential insulation. A modeling and inventory study examining the nation's changing fuel mix found that wood-fueled PM emissions dominate health and air quality impacts of residential combustion, followed by the mix of pollutants (NOx, NH_3, PM) from gas. We note that proper characterization of the impacts of gas combustion relative to other fuels requires multipollutant evaluations. Wood and, in some states, gas combustion now has greater impacts than coal. A study across California showed wood smoke and food cooking to be significant contributors to UFP ($PM_{0.1}$) among other sources. Chemical evaluations show how fog processing influences regional PM chemistry from IRC and the influence of IRC on organic PM, dominated by wood smoke. Evaluations demonstrate that nonresidential use of natural gas can have greater impacts than residential use. A reconstruction of historical black carbon emissions demonstrated the reductions are partially attributable to switching from fuel oils to natural gas, among other, simultaneous changes. Another study showed the prevalence of fossil and biomass black carbon concentrations but was unable to distinguish IRC from other uses of fossil gas.

We found no studies that presented a comprehensive lifecycle assessment of emissions, concentrations, or health impact from different fuels used for IRC. We expect that the upstream component of petroleum fuels production is likely a significant emitter that should be addressed before comparing between wood and petroleum fuels. (Buonocore & Salimifard (2021) noted but did not evaluate this.)

We include here the few studies found on the confounding effects of cooked products compared to the fuels or appliances on which they are cooked. Meat cooking products make up a modest portion of the observed UFP and black carbon concentrations.

2.3.6.2 Literature Review

How do the impacts of residential combustion vary by region?

Karagulian et al. (2015) summarizes the results of a systematic review of source apportionment studies on PM_{10} and $PM_{2.5}$ performed in cities worldwide. It usefully includes a summary database of results from these studies available from the World Health Organization. It found that, globally, 25% of urban ambient $PM_{2.5}$ air pollution comes from traffic and 20% from domestic fuel burning, which includes a mix of wood, coal and gas fuel for cooking or heating and also includes effects of secondary PM formation. It also includes the results of numerous source apportionment studies conducted in the United States. Based on these, it found that the population-weighted average source contribution from residential combustion to total $PM_{2.5}$ in the United States is 12% in urban sites. Although this is based on a fuel mix, the focus on urban areas in the United States should weight the results away from contribution of fuels less common in urban areas, such as wood or propane, but also include additional influences of urban sources such as busy roadways on the relative importance of IRC emissions.

Penn et al. (2017) used the Community Multiscale Air Quality (CMAQ) model to simulate PM and O3 concentrations across the continental United States for 2005. It grouped sources together and included all residential fuel types, aggregated to county level for apportionment to states. It then performed health impact modeling to estimate premature mortalities. It includes attribution to source sector but not fuel. It considered impacts from electricity generating units (EGU) and residential combustion (RC) sources, "including oil and natural gas-burning furnaces or wood-burning stoves to heat homes." The conclusions included an estimate of 21,000 premature mortalities per year from EGU emissions (primarily from sulfur dioxide emissions forming secondary PM, mostly attributable to emissions in eight states reliant on coal combustion) and 10,000 premature mortalities per year from RC emissions. The air quality and health impacts from IRC are due to primary $PM_{2.5}$ emissions, and the vast majority of primary $PM_{2.5}$ emissions are associated with wood burning. Health impacts are tied primarily to states with large populations and where wood combustion is common. States with high home heating emissions near or upwind of highly populated areas include Ohio, California, Maryland, and New York. It observes that both IRC emissions and impacts are tied to population. It found that deaths from IRC exceed those from EGUs for states in the Northeast and West Coast where population density is high, EGU coal combustion is limited, and wood or oil is used for home heating. IRC impacts are also seasonal, as emissions primarily occur in cold weather. IRC related mortalities are 20 times higher in cold than warm months, and are greatest for January in the Northwest, Midwest, and Northeast. Although the study does not apportion impacts by fuel, it clearly relates health impacts to wood combustion.

Further work could build on existing Supplementary Material[13] to update the modeling period and attribute impacts to different IRC fuels.

How have IRC impacts changed over time?

Kirchstetter et al. (2017) reconstructed historical black carbon concentrations at urban locations in the United States. This paper does not directly attribute black carbon concentrations to individual fuels but does demonstrate the changes in black carbon concentrations, and thus climate forcing, from transitioning to other fuels, including natural gas and electricity. It estimated black carbon concentrations over the period from the mid-1960s to the early 2000s and found annual average black carbon concentrations in New Jersey and California decreased from 13 to 2 $\mu g/m^3$ and 4 to 1 $\mu g/m^3$, respectively, despite concurrent increases in fossil fuel consumption. Similar reductions were seen in ten states across the United States. The major takeaway is that transitioning to cleaner fuels used for wintertime heating has occurred and is responsible for the dramatic reductions in black carbon. For example, beginning in the early 1970s, distillate fuel oil in New Jersey's residential sector was substituted with natural gas and electricity. New Jersey's greater reliance on black carbon-producing heavy fuel oils and coal in the 1960s and early 1970s and subsequent transition to cleaner fuels explains why the decrease was larger in New Jersey than California.

Buonocore & Salimifard (2021) used modeling and emissions inventories to reconstruct the changes in ambient $PM_{2.5}$ health impacts (and thus ambient concentrations) from U.S. stationary fuel combustion from 2008 to 2017. It concludes IRC ambient impacts are driven by biomass and wood, while "At the state level, biomass and wood combustion has supplanted coal as the leading sources of mortality impacts from fuel combustion in many states." It discusses how the impacts of different fuels have shifted over this period. The major fuel consuming stationary sources included are industrial boilers, commercial and residential buildings, and electricity generation. Emissions and mortality are resolved at the state level. Fuels include coal, gas, wood and biomass, and oil. Over the period studied, the relative contribution to health impacts among stationary sources changed. In 2008, the health impacts of air pollution from stationary sources were largely driven by coal combustion. By 2017, the health burden of stationary air pollution sources was shared among a mixture of source types and fuels including residential and industrial gas and biomass and the remaining coal-fired electricity generation. It concludes that "[n]ationwide, in 2017, health impacts of [and thus concentrations from] biomass and wood combustion are higher than combustion of coal and gas individually. Industrial boilers had the highest emissions and health impacts, followed by residential buildings, electricity, and then commercial buildings." Results show that biomass and wood are the leading sources of stationary source air pollution health impacts in 24 states, and that the total health impacts of gas combustion surpass coal in 19 states and the District of Columbia. Biomass and wood combustion was the largest contributor to health impacts from residential buildings, largely driven by primary $PM_{2.5}$ emissions, but decreased over the study period. In 2017, the highest contributing sectors were industry, industrial boilers, and residential heating. The health

[13] Available at https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5332198/

impacts from residential heating in 2017 are primarily driven by emissions of $PM_{2.5}$ from biomass and wood, followed by a mix of NOx, NH_3, and $PM_{2.5}$ emitted from gas.

What else affects or confounds IRC's air quality contribution?

Another modeling study, Levy et al. (2016), used the Community Multiscale Air Quality (CMAQ) model to determine air quality benefits of improved residential energy efficiency. It found that annual reductions in direct residential combustion emissions of 30 million tons of CO_2, 25,000 tons of NOx, 10,000 tons of SO_2, 1,300 tons of VOCs, and 600 tons of primary $PM_{2.5}$ could be achieved with improving residential building insulation and other strategies to improve residential energy efficiency. It estimates that annual residential natural gas consumption would be reduced by 360 billion standard cubic feet (9% reduction), LPG/propane consumption by 490 million gallons (10% reduction), and fuel oil consumption by 480 million gallons (12% reduction). Both the absolute and percentage changes vary significantly across states. Although it computes health related impacts and modeled concentrations and changes, these are not reported. Nor does it break out impacts by individual fuels.

Yu et al. (2018) (introduced under the natural gas heading, Section 2.3.3) used a chemical transport model to measure regional concentrations and source contributions for PNC and $PM_{0.1}$ in California. It found nonresidential natural gas combustion (38-74%) made the largest single contribution to PNC concentrations at the ten regional monitoring locations, followed by nucleation (6-14%), wood smoke (1-8%), food cooking (1-9%), and mobile sources (4-8%). In contrast, wood smoke (25-49%) was the largest source of $PM_{0.1}$ in the SFBA followed by mobile sources (15-33%), nonresidential natural gas combustion (13-28%), and food cooking (4%-14%). Non-residential natural gas combustion (42-57%) was the largest $PM_{0.1}$ source at the South Coast Air Basin sites, followed by traffic sources (16-35%) and food cooking (6-14%). Contributions from cooking and mobile sources are enhanced in $PM_{0.1}$ vs. PNC, with the cooking source accounting for 15% of $PM_{0.1}$ at Santa Rosa and mobile sources (gasoline + diesel) accounting for 34% of PM0.1 at the Central LA site, followed by 33% of $PM_{0.1}$ at Livermore site. Wood smoke and aircraft are the major sources of $PM_{0.1}$ OC in Fresno and East Oakland during the winter of 2016. Wood burning contributions PNC are less dominant in central California because the size distribution of particles emitted from wood combustion peaks at 100-300 nm.

Chen et al. (2018) investigates how PM_1 organic sources and composition change with residential burning and the presence of fog both in wintertime San Joaquin Valley, CA. Outdoor air quality measurements are attributed to residential burning via four factors of organic aerosol identified by PMF analysis of measurements in Fresno. Biomass burning organic aerosol contributes 9% of organic aerosol mass on high-fog days and 27% of organic mass on low-fog days. Secondary organic aerosol (SOA) formation at Fresno is strongly affected by persistent fog stagnation and high humidity impacts on particles leading to enhanced organic aerosol concentration. Organic aerosol components contribute the largest fraction of submicron particles. No specific residential fuels are discussed.

Ciarelli et al. (2017) was designed to evaluate a modeling scheme for biomass-burning-like organic aerosol in a photochemical air quality model (CAMx). It is not a U.S. study but addresses residential combustion precursors for primary and secondary organic PM that could apply to the United States. It notes that there are higher organic PM concentrations in urban areas due to traffic, cooking, and heating, while residential combustion, particularly wood burning is responsible for around 60–70% of SOA formation. It found the overall contribution of residential combustion to organic PM concentrations in Europe varies between 52% at stations in the UK and 75–76% at stations in Scandinavia. It also investigated the contribution to OA from residential combustion precursors in different range of volatilities. Overall, residential heating emissions drive the organic PM composition, with the primary biomass burning component averaging 65% (range 46-77%) of the total primary organic fraction. However, both model and observations suggest that OA was mainly from secondary formation, at 62% (range 32 to 88%). 12 to 64% of the total residential-heating-related OA is from primary biomass burning emissions, higher in northern areas.

Yoon et al. (2018) created winter and nonwinter composites for elemental carbon (EC, essentially black carbon) and used the ^{14}C abundance in the EC fraction to quantify the relative contributions of fossil to biomass carbon across the San Francisco Bay Area in 2011-2012. This paper distinguishes the average biomass burning contributions to EC of 48 ± 8% and 41 ± 5% for winter and nonwinter seasons, respectively. It also notes that ambient concentrations of EC are approximately two to three times higher during the winter compared to the nonwinter season and the impact of governmental regulations including the Bay Area Air Quality Management District's Wood-Burning Device Rule (Bay Area Air Quality Management District (BAAQMD), 2020). This study uniquely resolves biomass EC contribution. However, it cannot distinguish the gas contribution from IRC and other sources.

Particularly for cooking appliances, a confounding issue may be air pollutant concentrations and emissions from the cooked product versus the cooking appliance, although this was rarely addressed. We found only one study (Kleeman et al., 2009) that directly addressed this. It collected size-resolved samples of ambient PM during a severe winter pollution episode at three sites in the San Joaquin Valley of California and analyzed for organic compounds. Samples were size segregated into six particle sizes, including UFP ($PM_{0.1}$). Total ultrafine particulate matter concentrations were dominated by contributions from wood combustion and meat cooking. Most ultrafine EC (black carbon) was found to be from petroleum combustion, with relatively minor contributions from biomass combustion and meat cooking. However, wood combustion and, to a lesser extent, meat cooking were identified to be significant sources of ultrafine organic carbon during the pollution episodes.

Sevimoğlu (2020) did estimate meat cooking emission factors. Although its focus was air pollution sources in Istanbul related to residential emission reduction strategies, particularly for coal, its findings on emissions from meat cooking are likely to be applicable to the United States in comparison to emissions rates from the appliance itself. It found, "[c]harbroiling extra lean meat produce fine aerosol emissions of 7 g/kg of meat cooked. In contrast, frying meat generate fine aerosol emissions recorded at 1 g/kg of meat [31]. The meat consumption per person was about 13.07 kg per year and chicken meat consumption was about 19.43 kg per year in 2013 in Istanbul."

Yu et al. (2018) also found that food cooking contributed between 4-14% of UFP ($PM_{0.1}$) emissions in San Francisco Bay Area and 6-14% of $PM_{0.1}$ emissions in greater Los Angeles urban area (SoCAB).

2.4. Health Impacts of IRC

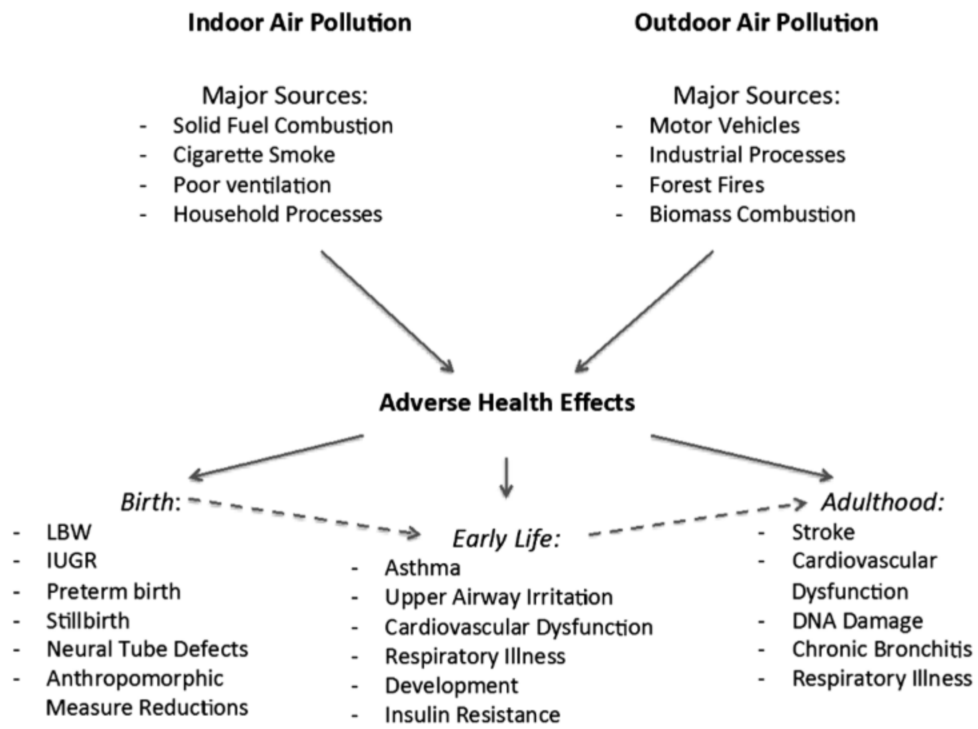
This section focuses on health impacts resulting from indoor and outdoor exposure to air pollutants generated by IRC.

A large body of research on the detrimental health effects of exposure to air pollution from all sources provides strong evidence that long-term exposure to ambient $PM_{2.5}$, ambient ozone, and household air pollution contributes to premature mortality and increased risk of illness from five chronic noncommunicable diseases: ischemic heart disease, stroke, chronic obstructive pulmonary disease (COPD), lung cancer, and type 2 diabetes; and one group of communicable diseases: lower respiratory infections (LRIs), such as pneumonia (Health Effects Institute, 2020). Evidence also exists of an association between household air pollution and increased asthma exacerbation, particularly if using gas for cooking or heating [e.g., Lee et al. (2020) and Lin et al. (2013)]**;** however, that evidence has been deemed insufficient regarding asthma development (Health Effects Institute, 2020).[14] Additionally, evidence is growing on the association between long-term exposure to air pollution and adverse birth outcomes (low birthweight, preterm birth, and still birth) (Health Effects Institute, 2020; Lee et al., 2020), as well as neurodevelopmental and neurocognitive outcomes, including cognitive decline (Clifford et al., 2016; Schroeder, 2011; Zare Sakhvidi et al., 2022), chronic kidney disease (Tsai et al., 2021), and gastrointestinal inflammatory diseases (Kaplan et al., 2010; Salim et al., 2014). Short-term exposure to high levels of air pollution can exacerbate asthma and cardiopulmonary symptoms (Health Effects Institute, 2020). Detrimental health effects of exposure to air pollution are experienced throughout the life-course as illustrated in Figure 13 (Farmer et al., 2014). The biological mechanisms underlying the adverse health effects of exposure to air pollutants are unclear, but differences in effects by fuels are apparent (Sussan et al., 2014)[15] and have been found in epidemiological studies comparing effects of PM from different sources (Hime et al. (2018). Therefore, 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).

[14] Studies do not always fully characterize the asthma outcome (asthma induction or asthma exacerbation). Asthma exacerbation is more likely to be assessed.

[15] We note that this study focused on cow dung vs wood.

Figure 13. Summary of Adverse Health Effects from Exposure to Air Pollution



Source: Farmer et al. (2014)

What did we review?

We reviewed the full text of 239 articles identified as potentially relevant during screening; 212 were peer-reviewed publications (83 review studies and 129 primary research studies), and 27 were publications from gray literature. We identified 93 peer-reviewed publications (51 review studies and 42 primary research studies) and 2 publications from gray literature as relevant to this research area. More than half of these articles did not focus on specific health effects associated with IRC but rather provided background information on health effects of pollutants emitted by IRC sources (e.g., $PM_{2.5}$, NO_2). In this section, we synthesize important findings from relevant publications, particularly those that focus specifically on health effects associated with IRC.

Retrieved literature on health impacts of IRC was dominated by studies conducted in contexts not relevant to the United States or they examined air pollution sources or air pollutants without a direct link to IRC. Additionally, potentially relevant literature mainly focused on biomass combustion and interventions to reduce exposure in developing countries. Finally, as noted in several review studies, the heterogeneity in the available literature severely limits evidence synthesis and generalizability of findings. Below, we offer a summary of key findings (Section 2.4.1) and in-depth discussion of the identified literature on health impacts of indoor combustion of natural gas (Section 2.4.2) and wood fuels (Section 2.4.4). In Section 2.4.5, we summarize results from the studies that focused on IRC sources not characterized by fuel type. We did not encounter studies of health impacts from IRC of other fossil fuels (e.g., propane, kerosene, oils) or other non-fossil fuels (e.g., synthetic fuels, RNG, biofuels) for the United States.

2.4.1 Summary

2.4.1.1 Health Impacts of Indoor Exposure to IRC Air Pollution in the United States

How robust is the available literature?

Indoor exposure to air pollution is a major contributor to total exposure (Rosário Filho et al., 2021). Household air pollution from solid fuels was identified among the 10 leading health risk factors by the Global Burden of Disease Study 2019 (GBD 2019 Risk Factors Collaborators, 2020), although its ranking has declined since 1990, while the ranking of ambient $PM_{2.5}$ has increased. As estimated for the GBD studies, however, household air pollution has a negligible impact in high income countries, including the United States. Of note is that GBD studies estimate household air pollution from home exposure to $PM_{2.5}$ emissions from solid fuel combustion for cooking; this likely leads to an underestimate of impacts because the impact of exposure to other pollutants and the impact of $PM_{2.5}$ originating from indoor combustion from other fuel sources (e.g., kerosene) or solid fuel combustion for heating or hot water are not included (Health Effects Institute, 2020). Studies with broader household air pollution scope [e.g., Lee et al. (2020)], however, also place the burden of household air pollution mainly on low-income and middle-income countries (Lee et al., 2020).

Existing literature is dominated by studies on the impact of residential solid fuel combustion and evidence specifically focused on health impacts of IRC is limited in developed countries, particularly in the United States (Thompson, 2022). For example, a recent systematic literature review and meta-analysis conducted by Guercio et al. focused on detrimental effects of residential solid fuel combustion on children's respiratory health in developed countries. Of 5,932 retrieved studies, only 59 examined effects of indoor air pollution and 15 examined the effects of related outdoor air pollution. (Guercio et al., 2021) Similarly, in a systematic review and meta-analysis examining adverse health effects of household air pollution from cooking or heating, 80% of included studies were from low-income and middle-income countries (Lee et al., 2020).

Furthermore, the heterogeneity of available literature (study design, target populations and sample size, exposure assessment, outcome assessment, control for confounders and co-exposures) hinders evidence synthesis and generalizability of findings.

What are the findings from studies conducted in North America or comparable contexts?

Several studies have shown that indoor exposure to NO_2 and gas cooking can exacerbate children's asthma symptoms and wheeze and may increase lower respiratory tract illnesses and reduce lung function, particularly in the absence of ventilation and for children living with asthma or allergies. Evidence from studies in adults, however, is limited and inconsistent. Differential responsiveness due to genetic factors, as well as potential confounding by environmental tobacco smoke and indoor pollutants from outdoor sources and exposure misclassification, due to use of proxies or absence of data on ventilation and other factors, may influence the inconsistencies in results. In spite of the mixed results, researchers recommend that ventilation be used when cooking with gas appliances.

Indoor exposure to air pollutants from wood combustion is associated with lower respiratory infections in children and may be associated with upper respiratory infections, wheeze, and cough. For example, results from a recent randomized trial examining interventions to reduce indoor $PM_{2.5}$ concentrations in rural U.S. homes heated with woodstoves showed increased odds of an LRI diagnosis for an increase in indoor $PM_{2.5}$ concentrations; this analysis controlled for exposure to outdoor $PM_{2.5}$ and smoking.

HONO and UFP**,** which IRC sources can emit, may exacerbate asthma but adverse health effects from indoor exposure to these pollutants are understudied, particularly research targeting specific effects from IRC sources. Existing evidence is limited and inconclusive.

Harmful health effects from exposure to CO, formaldehyde, PAHs, and other VOCs are known, but several potential sources of these pollutants besides relevant IRC sources (e.g., smoking, candle burning, building materials, consumer products, etc.) exist, and we reviewed no studies that isolated the health effects due to exposures originating specifically from IRC.

Children, particularly indigenous children, and other susceptible populations (individuals living with asthma or cardiopulmonary diseases, pregnant women, older individuals), and people in low wealth or rural communities are the most vulnerable to detrimental health effects from exposure to pollutants from IRC.

2.4.1.2 Health Impacts of Outdoor Exposure to IRC Air Pollution in the United States

How robust is the available literature?

Exposure to outdoor air pollution is a leading global health risk, particularly for cardiovascular and respiratory diseases, accounting for a loss of life expectancy comparable to that of tobacco smoking (Lelieveld et al., 2020). Specifically, for the United States in 2015, Lelieveld estimated 283,000 excess deaths due to ambient $PM_{2.5}$ and ozone; 230,000 excess deaths due to anthropogenic emissions; 194,000 excess deaths due to fossil fuel combustion. On a global scale, however, the health impact of outdoor air pollution from IRC is most important for developing countries. In fact, in a modeling study restricted to emissions from cooking with solid fuels, Chafe et al. (2014) used 2010 GBD data to model the proportion of ambient $PM_{2.5}$ produced by households and estimated that, for the "High Income North America" region, the population-exposure weighted concentration of ambient $PM_{2.5}$ attributable to household cooking with solid fuels was negligible, with 0 estimated deaths and disability-adjusted life years in 1990 and 2010. (Chafe et al., 2014)

Among seven review studies that were considered relevant for health effects of outdoor exposure to combustion air pollutants, only two studies included specific results for outdoor air pollution from IRC (Guercio et al. (2021); Rokoff et al. (2017)), while the remaining studies discussed health impacts from exposure to pollution generated by IRC in general. However, as noted by Guercio et al., the absence of additional evidence for the health impacts of different sources does not mean that they are not associated with detrimental health effects (Guercio et al., 2021).

None of the seven U.S. modeling studies that we reviewed fully isolated the IRC impact on health from *all* IRC sources (wood, gas, etc.). One study evaluated combined impacts of residential and commercial indoor combustion. One reported health impacts from residential gas use only. Two characterized health impacts from RWC. Other studies included emissions that may not be entirely indoor combustion related (e.g., heating appliances placed outdoors, cooking outdoors, cooking emissions not from fuel combustion).

What are the findings from studies conducted in the United States?

Best nationwide mortality burden estimates place impact of outdoor exposure to IRC air pollution at fewer than 10,000 deaths per year, which corresponds to <0.5% of annual all-cause mortality and <5% of annual outdoor air pollution-related mortality in the United States (see Section 2.4.5.2.2 for details). A modeling study in California showed that replacing gas appliances by electrical appliances would have a minor impact on mortality, corresponding to ~0.1% reduction in annual all-cause mortality in the study area (see Section 2.4.2.2.2 for details). Another modeling study in the Pacific Northwest estimated that a 100% reduction in residential wood smoke emissions could result in a ~0.5% reduction in annual all-cause mortality in the study area (see Section 2.4.4.2.2 for details).

Mortality impacts related to $PM_{2.5}$ exposure from residential buildings show a decreasing trend in the past decade, driven by reductions in wood and biomass combustion.

Sparse literature in the context of IRC has found consistent associations between higher pollution levels and detrimental respiratory effects in children, including worse lung function for children with asthma, but mixed results for asthma prevalence, cough, and wheeze.

The identified review studies that focused on outdoor exposure impacts of IRC largely conclude that emission controls targeting indoor air quality that focus on curbing indoor emissions (e.g., through venting), but not reducing emissions overall, may lead to community-level adverse health effects from exposure to outdoor air pollution. Additionally, a study conducted in a small community in Montana showed benefits for children's respiratory health (including, but not limited to, for children with asthma) from a woodstove replacement program that translated into decreased winter ambient $PM_{2.5}$ in the community.

2.4.1.3 Gaps found in research on health effects from indoor and outdoor exposure to IRC air pollution

We note the following as gaps and needs specifically addressing health impacts from IRC due to exposure indoors and outdoors identified through our research:

- 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.
- Poor understanding of potential differences in pollutant toxicity given fuel sources (e.g., $PM_{2.5}$ from different sources) and interactions with co-exposures or effect of climatic differences.
- None of the reviewed U.S. modeling studies relevant for health impacts of IRC from outdoor exposure fully isolated IRC.
- Studies on health impacts of outdoor exposure to air pollutants generated by IRC primarily focus on mortality and morbidity associated with wood combustion and $PM_{2.5}$ exposure. There is lack of evidence on mortality or morbidity impacts of other sources/pollutants.

Sections 4.2 and 4.3 contain detailed recommendations on studies and data collection needed to address these gaps.

2.4.2 Natural Gas

2.4.2.1 Summary

Exposure to indoor NO_2 and other pollutants from natural gas combustion can exacerbate asthma symptoms and wheeze in children. It may also increase lower respiratory tract illnesses and reduce lung function parameters in children, particularly in the absence of ventilation and for those living with asthma or allergies. Such evidence from studies in adults is limited and inconsistent.

Among reviewed studies, only one examined the impact of outdoor exposure to air pollutants associated with indoor natural gas combustion.

2.4.2.2 Literature Review

2.4.2.2.1 Indoor exposures

Strachan (2000) reviewed the literature regarding the role of environmental factors in asthma prevalence and asthma attacks and concluded that there was inconclusive evidence for increased asthma risk due to gas cooking. A narrative literature review conducted by Breysse et al. (2010) suggested that exposure to NO_2 was significantly related to asthma morbidity in urban environments, but evidence was still insufficient. Heinrich (2011) reported results from an earlier systematic review and meta-analysis of three population-based studies in children which found an association between gas cooking and non-specified risk of asthma (unadjusted risk = 1.20, 95% confidential interval (CI) 1.11–1.30) and wheezing (1.12, 95% CI 1.04–1.20). Additionally, this author also reported that results from studies in adults were inconsistent. Heinrich concluded that results for asthma (onset and exacerbation) and other respiratory endpoints, including lung function, were inconsistent, but as a precaution, recommended extensive use of ventilation when cooking with gas appliances.

Lin et al. (2013) conducted a meta-analysis on effects of indoor NO_2 and gas cooking (without other combustion sources) on incidence or prevalence of asthma and wheeze in children. Their analysis showed that gas cooking was associated with asthma (summary OR = 1.32, 95% CI 1.18-1.48) while a 15-ppb increase in indoor NO_2 had a positive, non-statistically significant association (summary OR = 1.09, 95% CI 0.91-1.31). Additionally, indoor NO_2 was associated with current wheeze (summary OR 1.15, 95% CI 1.06-1.25). The authors state that the estimates "did not vary much between regions", however a univariate stratified analysis showed a lower non-statistically significant summary odds ratio for 6 studies in North America with high heterogeneity among studies (summary OR = 1.12, 95% CI 0.73-1.73). Results for the association between gas cooking and current and lifetime wheeze were not significant for all studies (summary OR = 1.06, 95% CI 0.99–1.13), but were significant for 20 studies across regions reporting proportion of gas cooking >= 30% (summary OR = 1.09, 95% CI 1.01–1.16).

A randomized controlled trial in New Zealand conducted by Howden-Chapman et al. (2008) found that significant reductions in symptoms of asthma, days off school, healthcare utilization, and visits to a pharmacist were observed among households with nonpolluting heaters.

Studies conducted in Europe have shown inconsistent results for development of asthma and gas cooking or heating. According to Heinrich (2011), "the most consistent finding for an induction of asthma in childhood is related to exposure to environmental tobacco smoke, to living in homes close to busy roads, and in damp homes where are visible molds at home."

Fuentes-Leonarte et al. (2009) reviewed literature on indoor air pollution and children's respiratory health and found that most studies in developed countries reported detrimental effects of indoor gas combustion on cough/wheeze but not on respiratory infections. Lin et al. (2013) report results from a previous meta-analysis by Hasselblad et al. which showed a positive association between lower respiratory infections (LRIs) in children (OR=1.18, 95% CI,1.11–1.25) for a 15-ppb increase in indoor NO_2. Further, Li et al. (2006) found that a significant 50% increased annual risk of lower respiratory symptoms in children was associated with a 15-ppb increment in NO_2 exposure. Coker et al. (2015) conducted a cross-sectional analysis using data from a sample of children drawn from NHANES (1988–1994). Among children under 5 years of age, using gas stoves for heating and cooking rather than just for cooking showed double odds of pneumonia in the past 12 months (aOR: 2.08, 95% CI: 1.08–4.03) and significantly higher coughing (aOR: 1.66, 95% CI: 1.14–2.43). Additionally, children living in homes where gas stoves were used for heating without ventilation had significantly higher odds of pneumonia (aOR = 3.06, 95% CI:1.32–7.09) and coughing (aOR = 2.07, 95% CI: 1.29–3.30) than those living in homes where gas stoves were used only for cooking and with ventilation.

Moshammer et al. conducted a study of ~24,000 children from Europe and North America and found that gas cooking was associated with a small reduction in lung function parameters, but effects were only significant for forced vital capacity (0.6%) and forced expiratory volume in 1 second (0.7%) in the (unadjusted) basic model; they were slightly stronger in the basic model excluding North America participants and slightly weaker in the adjusted model. When results were stratified by atopic status, associations were stronger for allergic children. (Moshammer et al., 2010)

A study in Europe (Amaral et al., 2014) showed increased bronchial responsiveness to gas cooking in subjects with GSTM1 null genotype which may explain mixed findings regarding effects of gas cooking in exacerbation of asthma symptoms in adults. Genotyping was also considered in a study conducted by Morales et al. (2009) in Spain examining neuropsychological outcomes associated with use of gas appliances at home; the authors found detrimental effects on cognitive function and inattention symptoms and a stronger response in children with the GSTP1 Val-105 allele.

2.4.2.2.2 Outdoor exposures

Zhu et al. used EPA's BenMAP tool to model the impact of replacing gas appliances by electrical appliances for the year 2018 in California. They estimated decreases of 354 deaths (all-cause mortality), 304 cases of chronic bronchitis, and 596 cases of acute bronchitis associated with reducing emissions of primary and secondary $PM_{2.5}$ (Zhu et al., 2020). The estimated potential reduction in annual mortality represents approximately 0.1% of the total 270,000 annual deaths in California, in 2018, as reported by California Health & Human Services Agency (California Health and Human Services, 2021).

2.4.3 Other Fossil Fuels

We did not encounter studies linking indoor combustion of other fossil fuels (e.g., propane, kerosene, oils) to human health effects.

2.4.4 Wood Fuels

2.4.4.1 Summary

Evidence from reviewed literature shows that indoor exposure to $PM_{2.5}$ and other air pollutants from solid fuel/wood combustion is associated with lower respiratory infections in children and may be associated with upper respiratory infections, wheeze, and cough. Evidence regarding outdoor exposure to air pollution specifically from IRC of wood fuels is limited but indicative of detrimental impacts on children's respiratory health.

2.4.4.2 Literature Review

2.4.4.2.1 Indoor Exposures

Two recent literature reviews [Guercio et al. (2021) and Rokoff et al. (2017)] synthesized the health effects of exposure to indoor solid fuel combustion on children's respiratory health. Guercio et al. examined effects on asthma diagnosis (allergic and nonallergic), LRIs (bronchitis, bronchiolitis, pneumonia, and unspecified), upper respiratory infections (URI: colds, unspecified sore throat, throat infection, nonallergic rhinitis, and overall URI diagnosis), and respiratory symptoms (wheeze and cough). Considering studies from North America, results from meta-analyses found a nonsignificant negative association for asthma (10 studies, pooled RR 0.87, 95% CI 0.71–1.06), a significant positive association for LRI (5 studies, pooled RR 1.73, 95% CI 1.06–2.85), and nonsignificant positive associations for URI (5 studies, pooled RR 1.18, 95% CI 0.93–1.51), wheeze (11 studies, pooled RR 1.03, 95% CI 0.90–1.17), and cough (8 studies, pooled RR 1.07, 95% CI 0.98–1.18). Guercio et al. noted that previous systematic reviews and meta-analyses were conducted in developing countries and their results are not "directly comparable" since they examine the health effects of high indoor pollutant levels. Rokoff et al. conducted a narrative review focused on indoor woodstove combustion and found mixed results for associations with cough and wheeze and limited evidence for other children's respiratory outcomes.

For example, a new study by Walker et al. reported results from a randomized trial examining interventions to reduce indoor $PM_{2.5}$ concentrations in rural U.S. homes heated with woodstoves; controlling for outdoor $PM_{2.5}$ and smoking, but not other potential indoor sources of $PM_{2.5}$. In addition to woodstove combustion, this study found higher odds of children's LRI diagnosis (OR 1.45, 95% CI: 1.02–2.05) per interquartile range (IQR:25 μg/m3) increase in 6-d mean indoor $PM_{2.5}$ (Walker et al., 2022).

We did not review any research studies conducted in the U.S. that confirmed an increased risk of COPD and chronic bronchitis (Kurmi et al., 2010), cataract formation (Khanna & Khanna, 2020) or esophageal squamous cell carcinoma (Okello et al., 2019) associated with indoor solid fuel combustion, particularly wood smoke, found in developing countries. Amaral et al. (2018) (only) found a significant association for chronic phlegm among female never smokers, and among those who had been exposed for 20 years or longer. Regarding other adverse health effects, Rabito et al. (2020) observed positive associations between 0-72 hrs. of exposure to black carbon and increased systolic blood pressure.

As noted by Capistrano et al. (2017), there is insufficient epidemiological evidence to ascertain associations for low indoor exposures from IRC sources in developed countries. Additionally, in vivo and in vitro toxicology studies are needed to determine causal mechanisms between exposure and health outcomes; significant challenges are posed by the variability in chemical composition of air pollution originating from combustion of different fuels and the differences from cigarette exposure models, as well as the lack of standardization for smoke generation and delivery.

Lee et al. (2015) conducted a systematic review of immunomodulatory mechanisms of household air pollution from wood smoke combustion in developed countries and found detrimental effects on the immune system leading children to higher susceptibility to acute LRI. The authors suggested that PM may modulate the innate immune system "through a) alveolar macrophage-driven inflammation, recruitment of neutrophils, and disruption of barrier defenses; b) alterations in alveolar macrophage phagocytosis and intracellular killing; and c) increased susceptibility to infection via upregulation of receptors involved in pathogen invasion." (Lee et al., 2015)

2.4.4.2.2 Outdoor Exposures

Three review studies examined the health impact from outdoor air pollution from IRC (Guercio et al., 2021; Hime et al., 2018; Rokoff et al., 2017), specifically from indoor wood combustion.

Rokoff et al. conducted a narrative review focused on outdoor air pollution resulting from "community wood smoke" (ambient air pollution originated from indoor woodstove combustion) and found consistent associations between higher pollution levels and detrimental respiratory effects in children (URI, LRI and hospital admission for respiratory illness), no association with asthma prevalence but worse lung function for children with asthma, and mixed results for cough and wheeze. Additionally, this study also found that sparse results on potential detrimental effects on birth size and birth weight were inconclusive. (Rokoff et al., 2017)

A review by Hime et al. (2018), comparing health effects of ambient PM from five emission sources (including RWC), found some evidence of more harmful effects from exposure to PM from traffic and coal-fired power station emissions than from other sources, but the evidence was not conclusive overall. Ambient PM originating from RWC was associated with harmful effects on respiratory health, particularly for children. The authors noted that toxicological studies have shown that effects on lung immune defense are biologically plausible and that ambient concentrations of wood smoke can cause mild airway inflammation. Additionally, Hime et al. (2018) report results from a source-apportionment study using positive matrix factorization that indicated statistically significant detrimental effects on daily cardiovascular and emergency department visits from wood smoke from combustion heaters (RR for IQR increase in $PM_{2.5}$ = 1.029, 95%C.I. 1.018-1.037).

Guercio et al. who examined the impact of solid fuel combustion on children's health do not report summary conclusions for North American studies, but they cite a U.S. study on a small rural community impacted by wood smoke from indoor combustion which found reductions in reported wheeze and respiratory infections for a 5 μg/m3 decrease in average winter $PM_{2.5}$ (Noonan et al., 2012b). Additionally, Guercio and colleagues mention three cohort studies that reported at least one adverse respiratory effect associated with IRC and a large Canadian study that found a null association between wood smoke exposure and asthma risk. (Guercio et al., 2021) (Inclusive of other references noted therein.) Similarly, considering results from a woodstove replacement program, Noonan et al. reported no difference in children's respiratory health outcomes related to presence of a woodstove in the home, but a 5 μg/m3 reduction in winter ambient $PM_{2.5}$ concentrations was associated with improved respiratory and other symptoms and infections (wheeze, itchy/watery eyes, sore throat, cold, bronchitis, influenza and throat infection). (Noonan et al., 2011)

A U.S. modeling study (Regional Technical Forum, 2014) focused on health benefits of several scenarios of reductions in RWC for heating in the Pacific North West. This study estimated avoided mortality (200-500 annual deaths in 2017) associated with a scenario of 100% reduction in wood smoke emissions, and corresponding reductions in ambient $PM_{2.5}$, as well as avoided cases of upper and lower respiratory symptoms (6,700 and 4,600 cases, respectively). The estimated mortality reduction represents approximately 0.5% of the total 108,000 annual deaths reported for Oregon, Washington, and Idaho in 2017 by CDC (Centers for Disease Control and Prevention, 2021).

Zhang et al. modeled outdoor air concentrations of 16 PAHs across the continental United States. They applied an updated Community Multiscale Air Quality (CMAQ) model to quantify the contributions of different emission sources including residential wood combustion to the predicted

PAH concentrations and excess cancer risk in the United States in 2011 and apportioned contributions to nine sectors (including residential wood combustion); they found residential wood combustion contributed 16.2% of incremental lifetime cancer risk ILCR due to inhalation exposure of outdoor naphthalene and seven carcinogenic PAHs. (Zhang et al., 2016)

2.4.4.2.3 Sensitive Populations

Children, particularly indigenous children, and other susceptible populations (individuals living with asthma or cardiopulmonary diseases, pregnant women, older individuals), as well as people in low wealth, rural communities or African American households are the most vulnerable to detrimental health effects from exposure to pollutants from IRC, particularly PM from wood combustion. (Coker et al., 2015; Cortes-Ramirez et al., 2021; Walker et al., 2022; Zelikoff et al., 2002; Zhang et al., 2021)

Barros et al. conducted a review focused on American Indian/Alaska-Native (AI/AN) children and found "indoor use of wood for heating or cooking" as a major factor impacting these sensitive population due to increased risk of respiratory illness. (Barros et al., 2018) Lowe et al. reviewed studies conducted with Navajo children living on a reservation and noted that very limited evidence was available and but exposure to emissions from wood-burning stoves and cook stoves was among the risk factors for asthma that should be better studied. (Lowe et al., 2018)

A review by Po et al. of studies from rural locations in mostly developing countries (only one U.S. study) showed that significant associations between exposure to solid biomass fuels (including wood) and respiratory disease in rural women and children. (Po et al., 2011). Similarly, a review by Aithal et al. of studies conducted in low- and middle-income countries suggested detrimental effects on lung function in children from exposure to household air pollution. (Aithal et al., 2021)

2.4.5 Other Fuels and Non-fuel Specific

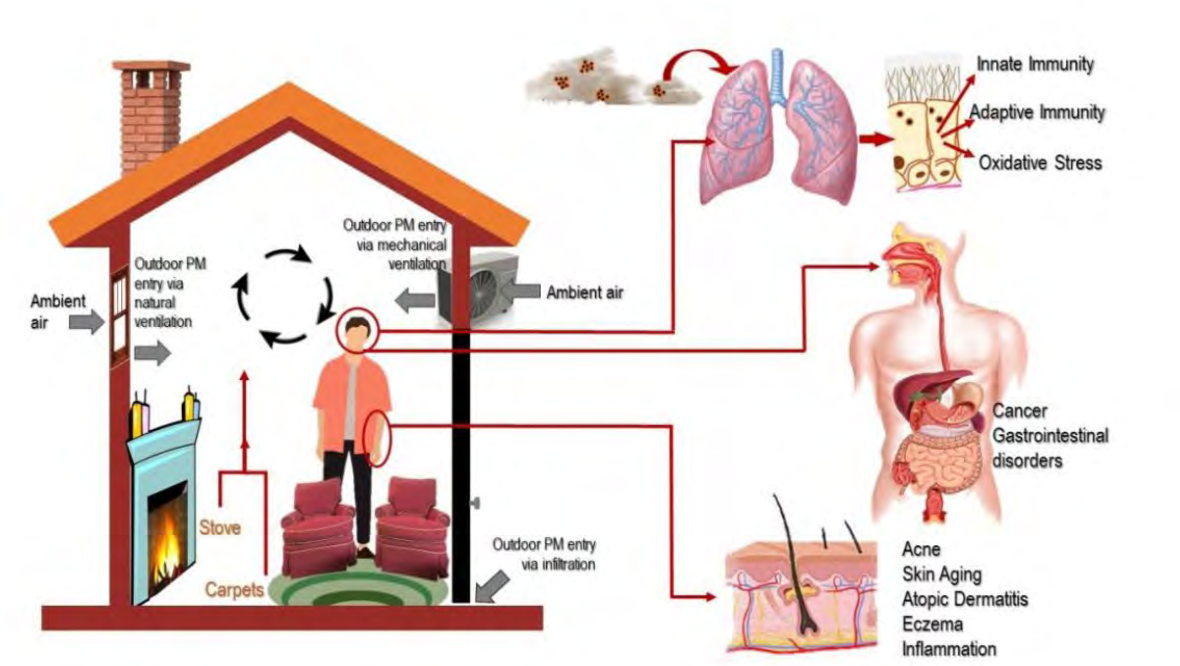
We did not review studies linking indoor combustion of other non-fossil fuels (e.g., biofuels, synthetic, RNG) to human health effects. We report on combined impacts from mixed fuels or fuel-unspecific impacts here.

2.4.5.1 Summary

Health effects of indoor and outdoor exposure to $PM_{2.5}$, CO, and VOC generated from IRC are usually examined in connection with wood combustion, while NO_2 is frequently used as a proxy for natural gas combustion. These pollutants, however, can be emitted by other IRC sources; for example, natural gas combustion can be a source of $PM_{2.5}$, and wood combustion can lead to NO_2 emissions. Additionally, it is challenging to differentiate the health effects associated with indoor exposure to IRC-related pollutants from those associated with other indoor pollutant sources (e.g., home or personal care products, bioaerosols) or with indoor pollutants originating from outdoor combustion pollution sources (e.g., traffic or wildfire pollution entering homes via ventilation); this contributes to the lack of evidence specific to the health effects of air pollutants from IRC sources. For example, as noted by Zhang et al. (2021), IRC associated with cooking and heating is one of the main pathways of indoor exposure to PM (the other pathways being bioaerosols and home or personal care products).

As illustrated in Figure 14, PM in indoor air (from different sources) can enter the body through several routes: inhalation, dermal absorption, or ingestion.

Figure 14. Main Pathways of Exposure to Indoor PM



Source: Zhang et al. (2021).
Note: IRC is one of the sources for indoor exposure to PM; health effects displayed on this schematic may not all be related to IRC exposure.

Given existing research (i.e., not necessarily linked to IRC), beyond the known detrimental health effects from exposure to pollutants from natural gas and wood combustion, and $PM_{2.5}$ and NO_2 specifically, that other pollutants generated by IRC [e.g., CO, formaldehyde, PAHs and other VOCs, HONO, UFP] have detrimental health effects is plausible. For example, HONO and UFP may exacerbate asthma but adverse health effects from indoor exposure to these pollutants are under studied, and existing evidence is limited and inconclusive. We also note HONO was not found in our research in the preceding subject areas.

Three modeling studies estimated exposure-related health impacts due to *outdoor* air pollution from *IRC sources not characterized by fuel type*. The magnitude of U.S. mortality burden attributable to outdoor exposure to $PM_{2.5}$ from IRC was estimated at fewer than 10,000 deaths annually by three studies modeling impacts.

2.4.5.2 Literature Review

2.4.5.2.1 Indoor exposures

Heinrich et al. (2011) cite two epidemiological studies that assessed HONO with mixed results and thus inconclusive. These authors also cite an expert elicitation on health effects of UFP conducted in 2009 that "stated a high likelihood for associations with aggravation of asthma for short-term exposure to ultrafine particles exposure only." (Including references therein.)

Weichenthal et al. noted that UFP have been shown to cause oxidative stress but “while a number of indoor UFP sources have been identified and thoroughly characterized, the potential health effects of indoor UFP exposures remain largely unexplored.” (Weichenthal et al., 2007) In a more recent study, Corsini et al. discuss the potential harmful effects of UFP, including toxicological evidence from in vivo and in vitro studies, but they state that “as far as we know, papers focusing specifically on UFP originating from residential biomass combustion and their impact on human health are still lacking.” (Corsini et al., 2019)

Exposure to other indoor combustion air pollutants such as CO, formaldehyde, PAHs and other VOCs has been associated with harmful health effects, including cancer and adverse effects on women’s reproductive health, birth and developmental outcomes (Zhang et al., 2021; Zhu et al., 2020) , but there are several potential sources of these pollutants besides relevant IRC sources (e.g., smoking, candle burning, building materials, consumer products, etc.) and we did not review any studies isolating the health effects due to exposures originating specifically from IRC. For example, Schroeder 2011 notes that PAHs have been shown to have harmful neurodevelopmental toxicological effects, but further research is needed (Schroeder, 2011).

2.4.5.2.2 Outdoor exposures

Based on data from the EPA NEI 2005, Caiazzo et al. estimated that long-term exposure to $PM_{2.5}$ associated with commercial/residential combustion sources was associated with 41,800 (90% CI 18,700-75,500) annual premature deaths due to cardiovascular diseases and lung cancer (Caiazzo et al., 2013). Considering emissions from residential combustion from the same inventory, Penn et al. (2017) estimated 10,000 annual premature deaths, mostly associated with primary $PM_{2.5}$ emissions from wood combustion. Fann et al. (2013) also estimated mortality for different sectors using data from 2005 NEI; although they do not report estimates for residential combustion, Penn et al. estimate that these correspond to approximately 8,000 annual premature deaths. Using the EPA NEI 2014 data, Thakrar et al. estimated that residential cooking and heating is one of five activities driving total mortality due to ambient $PM_{2.5}$ in the U.S., being associated with 8,600 annual premature deaths (Thakrar et al., 2020). These estimates of mortality burden comprise less than 0.5% of annual U.S. mortality [approximately 2,500,000 U.S. deaths in 2010., as reported by CDC (National Center for Health Statistics (U.S.), 2013)] and less than 5% of annual outdoor air pollution-attributable U.S. mortality [approximately 300,000 annual U.S. deaths, as estimated by (Lelieveld et al., 2020)].

Buonocore et al. examined the U.S. trends in mortality impacts due to exposure to $PM_{2.5}$ from different combustion sources (Buonocore & Salimifard, 2021). This study noted a decrease in total mortality impacts from residential buildings from 2008 to 2017 and confirmed the major contribution of biomass and wood combustion, mostly due to $PM_{2.5}$ primary emissions, followed by gas use, due to a mix of NOx, NH_3 and $PM_{2.5}$ emissions. As stressed by the authors, this study did not account for mortality or morbidity impacts of indoor exposures, of ozone and NO_2 outdoor exposures, and morbidity impacts of $PM_{2.5}$, ozone, or NO_2 outdoor exposure. Neither this study nor the other reviewed studies mentioned above report health impacts from specific fuel sources or the contribution of IRC to health impacts of climate change.

3 Limitations

Our conclusions should be viewed in the context of limitations of this research effort.

First, the research on IRC sources and impacts in the United States belongs in a broad adjacent research domain (e.g., literature on air pollution, environmental epidemiology, epidemiology of specific diseases), often conducted in contexts that are very distinct from the United States (e.g., literature focusing on low- and middle-income countries). This effort resulted in a profusion of article references returned by the search, of which we reviewed only a sample because a systematic review was beyond the project scope. We also found that only a small fraction of the retrieved articles was directly relevant to our research area of interest, further highlighting the "needle-in-the-haystack" challenge of this research effort. Although we expect some of the pertinent articles (possibly affecting our conclusions) may have been missed, we believe that use of NLP tools for automated prioritization purposes has helped minimize this issue (see Appendix A for details).

Second, because a systematic study quality assessment was not in our scope, some of our conclusions may have been based on lower-quality research (e.g., studies using very small samples, coarse representation of sources, ecological methods). We note, however, that our review prioritized articles from peer-reviewed sources when available for a given research area, which offers a measure of quality control, and review articles that in some cases have implemented study quality assessments to support their synthesis. Because of the targeted scope of this project, we emphasized the peer-reviewed literature, and thus likely have not included some relevant gray literature.

Third, we found the literature offers only partial answers regarding the impacts of IRC in the United States. This could be addressed by integrated modeling studies to generate relevant quantitative impact estimates. Because our scope was to document what is in the literature, rather than generate new estimates, we use information discovered by this research effort to propose future work that includes integrative modeling possibilities.

4 Recommendations for Future Research

Our recommendations for future work are organized around three lines of research requiring progressively larger amount 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 Section A.2.3 in Appendix A, approximately 10,606 article references were obtained from the bibliographic database searches and prioritized for review via NLP methods. Particularly, a large collection of articles retrieved from gray literature sources (see Section A.1.3.2) was not examined as part of this analysis due to the general focus on peer-reviewed literature. 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.

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. This process would generate further insights into data and methodological gaps of this literature.

4.2. Quantitative synthesis using existing data

A modeling study could estimate the impact of ambient IRC emissions in the United States nationally, or in key geographies, to address specific community concerns. This study could be based on existing inventory data, such as NEI, or existing modeling approaches such as EPA's National Air Toxics Assessment, but ideally could be refined to target individual appliances and fuels more robustly. The study could focus on outdoor air quality or health impacts, or both. Some study design aspects to consider include:

- Small-scale analysis (e.g., at the neighborhood or census block group level), which may be infeasible nationwide but feasible for individual areas;
- Use of air quality modeling techniques that can simulate primary and secondary pollutants and produce results at local scales;
- Use of BenMAP (United States Environmental Protection Agency [EPA], 2022b) for outdoor air pollution health impact modeling (both, mortality and morbidity). This tool is appropriate for small-scale simulation and contains collections of health impact functions for a range of pollutants, including $PM_{2.5}$ and ozone;
- Consideration of the impacts of increased electricity generation emissions, not just IRC burden assessment, and the impacts of different fuel alternatives. This study could explicitly include or exclude RWC, which Zhu et al. (2020) noted could have wintertime impacts comparable to all other sources combined;
- Finally, we note that the emissions data collected here, especially those presented in Table 3, Table 4, Table 5, Table 6, and Table 7 may be leveraged to improve future modeling work.

Other modeling studies relevant to IRC impacts in the U.S. could include:

- A study focusing on black carbon emissions from IRC, ideally by fuel type. This could involve creating an inventory and calculating the relevant climate impacts. Ideally, such a study could also include black carbon emissions from electricity generation for comparison. Black carbon is not included in the U.S. GHG inventory.
- A modeling assessment of indoor exposure and related health impacts. Existing mechanistic and statistical approaches could be used to examine health impacts from various sources in the indoor environment. The work could focus on children, rural populations, or other sensitive demographic groups.

4.3. Research requiring new data collection

Several new data collection activities could improve our understanding of emissions and indoor air pollution from IRC sources in the U.S. First, improved survey on quantities of fossil-fueled appliances in housing units to fill gaps identified in the RECS and other information, particularly on presence and use of unvented (or vented but not used) appliances or nonstandard and emerging fuels. Second, improved emission factors for IRC appliances, including exhaust and leakage, are needed. Third, 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.

Large scale, multipollutant, lifecycle assessments would provide insights into the relative benefits and detriments of different fuels. New data collection would be needed to support lifecycle assessment of climate and health benefits of existing and emerging fuel alternatives, including H_2 and RNG compared to electricity and fossil gas used in IRC.

New data collection is also needed to improve robustness and generalizability of research studies on health impacts from IRC. The following aspects could be considered in such a study:

- Prospective design, which is important for determining causality for chronic exposure and developmental health effects or effects on diseases with long latency (e.g., cancer and cardiovascular diseases);
- Data collection using the existing large nationally representative health survey instruments (e.g., NHANES, Medical Expenditure Panel Survey) or from large ongoing prospective cohort projects;
- Large sample size allowing for statistical power needed to analyze small effect sizes at the individual level;
- Representative populations to draw generalizable conclusions;
- Rigorous exposure assessment, including identification of source of pollutants, measurement of biomarkers of exposure, personal exposure monitoring and time-activity diaries, use of appliances and control measures (e.g., ventilation, hoods), simultaneous indoor and outdoor air pollutant monitoring;
- Rigorous outcome assessment, based on medical diagnoses and quantitative measures (e.g., lung function), rather than self-reported, nonspecific symptoms (e.g., cough, wheeze);
- Quantification of co-exposures, including detailed location information to help augment the survey with outdoor monitoring data;
- Control for main potential confounders (particularly environmental tobacco smoke, socioeconomic status, housing density);
- Expansion to several sources and health outcomes, given the intensity of resources needed for such studies.

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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. Manual screening approach and results are described in section A.3, while full text review and information extraction process is summarized in section A.4. Section A.5 describes additional data sources of information that have been consulted to support this review. Sections A.6 and A.7 provide details of the search strings and screening guidelines employed.

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 (National Library of Medicine [NLM], National Center for Biotechnology Information [NCBI], 2022) – an engine to search the MEDLINE (National Library of Medicine [NLM], 2022) collection of biomedical research articles from peer-reviewed sources assembled by the U.S. 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 Information Services, 2022) – 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, 2022b) – 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 available to the public. Google Scholar searches article full text and meta-data, which generally produces large results sets.
- Gray literature sources, such as websites of U.S. government agencies and other reputable sources (Appendix B provides the list internet domains searched);
- Articles published between 2000 and January/February 2022; and
- Articles in English language.

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 have been developed based on topic definitions, using synonyms developed with input from the American Lung Association and topic subject matter experts. In that, the topic subject matter experts conducted ad hoc searches to identify seed articles. The seed articles comprised examples of on-topic materials (i.e., positive seeds) and off-topic material (i.e., negative seeds) uncovered via these initial searches. The seed articles have been used as part of the comprehensive testing implemented to refine queries (e.g., the queries have been tested to ensure that the results contain the majority of the positive seed articles).

The queries have also been customized for 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.
- Gray literature queries have been processed using Google organic (Google, 2022a) search that limits the length of the search string to 32 terms. We have adapted the queries from the peer searches, using select key terms from each search set with Boolean operators (and, or, not) to form search strings accommodating the imposed word limit.

Table 12 summarizes the general structure of the queries. This research was originally organized around 6 topics rather than the 4 research areas presented in the body of this report. Appendix A contains the fully specified queries for each of the original 6 topics, their definitions, and their adaptations to the bibliographic database searched.

Table 12. Topic-Specific Query Structure

Research Area	Topic Definition	Query Identifier	Query Definition*
Research Area 1: IRC-based technologies, fuels, and appliances in use in the U.S. and their relative prevalence in homes **Research Area 2:** Emissions from IRC appliances; contribution of IRC to IAQ; interactions with other sources of pollution; and effects of interventions to reduce exposure	**Topic 1**: Technologies in use for combustion-based heating and appliances and their relative prevalence in homes **Topic 2**: Emissions profiles as designed, installed, or operated **Topic 3**: Contribution to IAQ, including effect variability, interactions with other sources of pollution, and effects of interventions to reduce exposure	1-3a	{Appliances} **AND** {Source} **AND** {Type}
		1-3b	({Appliances} OR {Source}) **AND** {Indoor Air Quality} **AND** {Type}
		4b	{Indoor Air Quality} **AND** {Type} **AND** {Exposure Reduction}
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 / 5a alt	({Appliances} OR|AND {Source}) **AND** ({Indoor Air Quality} **AND** {Outdoor Air Quality}) **AND** {Source Qualifier}
		5b / 5b alt	({Appliances} OR|AND {Source}) **AND** {Air Quality General} **AND** ({Source Qualifier} OR {Action} OR {Exposure Reduction}) **AND** {Type}
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}
		4c	{Indoor Air Quality} **AND** {Type} **AND** {Exposure Reduction} **AND** {Health Impacts} **AND** {Modeling}
	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}
		6b	{Indoor Air Quality} **AND** {Outdoor Air Quality} **AND** {Type} **AND** {Health Impacts} **AND** {Exposure Reduction} **AND** {Modeling}

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.6. OR|AND indicates variants of the query, the OR-query is less restrictive and the AND-query is more restrictive (ran if less restrictive query retrieved too many references).

A.1.3. Search Implementation

The final database searches were implemented in January 2022 and February 2022. The gray literature searches were implemented in March 2022. 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 execution of the searches on each bibliographic platform in our scope (topic numbers refer to the original scheme defined in Table 12):

- PubMed web interface has been used for the reference retrieval. Topic 4 (health impacts of IRC) search that focused on reviews (Query 4a in Table 12) has been restricted to review articles in PubMed, to better target the search;
- EBSCOhost web interface has been used for the reference retrieval. The searches have been conducted in in the following databases: E-Journals, Environment Complete, Energy & Power Source, and Academic Source Ultimate. References were further restricted by Publication and Document Type to academic articles and journals. Since we searched PubMed separately, there was no need to search Medline via EBSCO, and the other EBSCO databases we excluded contain content related to the fields of psychology, sociology, or education, which were less likely to yield relevant results;
- Google Scholar searches have been conducted using SerpAPI (SerpAPI, 2022) service. For each search string, we have retrieved the top 500 references, which corresponds to the set of results from the first 50 pages 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 PaperPile (Paperpile LLC, 2022) reference management service to automatically extract full meta-data for the result set, whenever possible. Full meta-data, including abstracts, have been obtained for approximately 70% of the references retrieved by Google Scholar;
- Google Scholar searches have been conducted for Topics 1-3 and 5 only. We have determined that the health-oriented Topics 4 and 6 have been sufficiently covered by PubMed and EBSCO.

All search results have been imported into EndNote (Clarivate, 2022). This tool has been used to remove multiple versions of the same reference within each topic. Table 13 summarizes the results of retrieval by topic (as performed using the original topic definitions).

Table 13. 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 1: Technologies in use for combustion-based heating and appliances and their relative prevalence in homes **Topic 2**: Emissions profiles as designed, installed, or operated **Topic 3**: Contribution to IAQ, including effect variability, interactions with other sources of pollution, and effects of interventions to reduce exposure	1-3a	3,767	8,228	7,544	22,021
	1-3b	4,426	too many results		
	4b	2,298	4,886	not searched	5,679
Topic 4: Health impacts of exposure to IRC	4a	1,088	566	not searched	1,350
	4c	921	335		
Topic 5: Contribution of indoor residential combustion to OAQ and GHG	5a	50	167 (restrictive query)	38,039	41,973
	5b	3,532	561 (restrictive query)		
Topic 6: Contribution of IRC to public health burden of OAQ or climate change	6a	915	408	not searched	1,826
	6b	833	39		

A.1.3.2. Gray Literature Sources

To conduct retrieval from gray literature sources, we have employed ICF's Google Scraper tool. Google Scraper captures and outputs the URLs and other meta-data, such as abbreviated document or web page titles, number of hits found by site, and whether items are duplicative of other results found via the same search, for the search results. The tool also downloads files found during the search, assigning each a unique file name that is recorded in the output file. Note that the article references captured via this mechanism are not formatted as bibliographic references. This prevents management of references using EndNote. Also note that some of the retrieved materials may have already been identified via bibliographic platform searches. Table 14 provides the summary of retrieval results from the gray literature sources. A full accounting is provided in Appendix B.

Table 14. Total Results of Retrieval by Topic Area and Gray Literature Domain

Number of Domains Searched	Number of Results		
	Topics 1-3	Topics 4 and 6	Topic 5
67	4512	2154	2962

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.4);
- Seed articles identified by topic subject matter experts using ad hoc searches or via other means (e.g., client communication, web resources tracked by subject matter experts). Peer reviewed and gray-literature articles found in this manner have been published very recently and, as a result, were not indexed/uncoverable by the searches;
- 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

As seen in section A.1.3.1, the number of article references returned by the topic-specific queries is on the order of thousands. Because this project was not intended as a systematic literature review (i.e., a review of all retrieved articles), we planned on reviewing a subset of identified references. To focus our efforts on most pertinent materials, we used natural language processing (NLP) methods for reference prioritization. NLP-based automation has been employed at four stages of the retrieved literature analysis: initial prioritization of the article references retrieved from bibliographic databases (section A.2.1); prioritization of article references during manual screening (section A.2.2); prioritization of references post-manual screening for future use (section A.2.3); identification of review papers for some of the topics (section A.2.4). We note that references retrieved from gray literature sources have not been automatically analyzed due to the lack of necessary meta-data (i.e., title and abstract text).

A.2.1. Initial Prioritization

We used positive and negative seed articles organized by our original topic areas (see section A.1.4) to fit three topic area-specific simple machine learning models.[16] The learning objective has been to discriminate between positive (i.e., on topic) and negative (i.e., off-topic) articles based on the title and abstract text. Once fit, each model produces a score that reflects the expected topic relevance

[16] Specifically, we fit linear Support Vector Machine (SVM) models.

of the article based on the title and abstract text. Liu's (2012) approach has been used to determine the optimal cutoff score for a positive prediction using the training data.

These initial models were used to process the references retrieved by the bibliographic platform searches (see section A.1.3.1) to prioritize article references for the manual review (see section A.3). Specifically, each retrieved reference has been scored by each model, and references with at least one score above the optimal cutoff have been promoted to the manual review pool. As such, there were unique 14,059 references prioritized for manual screening.

We note that the predictive ability of the models trained at this stage was not evaluated because compilation of additional set-aside testing data has been de-prioritized in lieu of the manual screening initiation.[17] However, we also note that a positive model prediction indicates a relevance *potential*. As such, only 14% percent 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.

A.2.2. Prioritization during Manual Screening

Manual reference screening has been implemented using ICF's litstream™ (ICF, 2022) review management tool. To improve efficiency of the manual screening process, we used active machine learning functionality (Varghese et al., 2019) in litstream™. Specifically, we employed the following the human-in-the-loop process:

1. Screeners judged 350 article references selected randomly from the litstream™ review pool of 14,059 references. A machine learning model with an objective to predict relevance to one or more topics was fit to this set and used to score the references not yet subjected to manual review.
2. Screeners judged two batches of 50 article references selected randomly from the remaining unreviewed pool. To facilitate learning, these sets contained references with a mix of relevance scores (50% most probable, 30% most uncertain, and 20% random sampling). Upon completion of this screening step, the machine learning model was re-trained and used to re-score the references not yet subjected to manual review. This step was repeated one more time, adding another 50 articles to the reviewed pool and updating the machine learning model once more.
3. Screeners judged the final set of 555 article references from the remaining unreviewed pool; these references were judged as most probable by the machine learning model fit upon completion of phase 2 above.

[17] We also note that the measurements of the predictive ability based on the data used for model fitting are not reliable and are biased upward.

A.2.3. Prioritization Post-Manual Screening

Upon completion of the manual screening stage in litstream™, there were 13,054 unscreened article references from the initially prioritized set as well as approximately[18] 56,806 unscreened references that were not initially prioritized. To facilitate future review efforts on these topics, we have used a larger set of all 2,087 human-assessed article references, comprised of 1,046 seed articles (see section A.1.4), 36 article used in screening pilots (see section A.3), and 1,005 articles screened in litstream™ (see section A.3.1) to fit state-of-the-art machine learning models[19] for each topic area. These models have been used to develop a higher-quality prioritization for the remaining unscreened article references.[20]

We used the AutoNLP service from the Hugging Face project[21] (Hugging Face, 2022) to develop four models with the following learning objectives: (1) predict relevance to Topics 1-3; (2) predict relevance to Topics 4 & 6; (3) predict relevance to Topic 5; and (4) predict overall relevance to one or more topics. For each learning objective, the article reference title and abstract text has been used to fit 15 candidate models differing in structure and training method, of which the best-performing model has been chosen. To support fitting and evaluation, the available human-screened article references have been split into a training set (79%, used to fit the candidate models), validation set (10%, used to select across candidate models), and test set (11%, used to evaluate performance). We report performance of these models in Table 15, along with the number of unscreened article references that were prioritized for future review using the optimal cutoff method (Liu, 2012).

[18] Approximate because the process included machine prioritization before complete deduplication.
[19] Specifically, we employed neural network-based machine learning models using variants of the transformer architecture. One of the first examples of this model type is the Bidirectional Encoder Representations from Transformers (BERT) model (Devlin, J., Chang, M.-W., Lee, K., & Toutanova, K. (2018). BERT: Pre-training of Deep Bidirectional Transformers for Language Understanding. *CoRR*, *abs/1810.04805*. https://doi.org/10.48550/arXiv.1810.04805) that have been shown to generate state-of-the-art performance for many NLP tasks.
[20] Recall that the initial screening model (described in section 4A.2.1) has a relatively poor predictive performance largely due to a small training sample size. We leveraged additional data generated during manual screening to improve the quality of the model used for prioritization.
[21] The Hugging Face project (https://huggingface.co/) offers access to many machine learning models developed by the research community to accomplish a range of natural language processing tasks, including text classification. The AutoNLP service offered by Hugging Face (https://huggingface.co/docs/autonlp/) further allows to fine-tune (i.e., customize) the available models using project-specific text data.

Table 15. Advanced Model Performance and the Number of References Above Optimal Cutoff

Model Learning Objective	Model Performance on the Test Set		Number of Unscreened References Prioritized for Review
	Precision	Recall	
Relevance to Topics 1-6	66%	70%	10,606
Relevance to Topics 1-3	55%	71%	4,133
Relevance to Topics 4 & 6	19%	62%	3,217
Relevance to Topic 5	39%	87%	2,053

Notes: Precision - share of references that were judged relevant by screeners among all references predicted to be relevant by the model (a value of 100% signifies perfect precision); Recall - share of references predicted to be relevant by the model among all references judged to be relevant by screeners (a value of 100% signifies perfect recall).

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.2.4. Identification of Review Studies

Because for Topic 4 we have been interested in identifying authoritative reviews of the IRC health effects literature, we additionally implemented a targeted search of the 3,217 article references prioritized for Topics 4 and 6 based on the advanced predictive model (described in section A.2.3). We used a disjunction of the following search terms: "review", "systematic", "meta-analysis", "meta analysis", "PRISMA", "Cochran", "PubMed", "publication bias", "synthes", "MEDLINE", "EBSCO", "SCOPUS", "Web of Science", "Web of Knowledge", "Google Scholar", "bibliographic", "database". We found 562 review article candidates that were added to the manual screening task.

A.3. Manual Screening

The manual screening process consists in review of article reference meta-data (e.g., title, abstract) by appropriately trained analysts to identify articles that warrant the full text review. In that, the screeners follow the guidance developed by the topic area subject matter experts. To ensure quality of the manual review, we provided screeners with specific training on the application of screening criteria for this project. Screeners completed a pilot screening assignment with a follow-up error analysis. The screener feedback on the pilots screening assignments was used to expand and clarify the screening guidance document. The final screening guidelines for each original topics are in Section A.7.

A.3.1. Title and Abstract Screening

We used ICF's litstream™ (ICF, 2022) review management tool to implement most of the manual screening process. In that, the screeners reviewed 1,005 article references[22] (prioritized as described in section A.2.1 and section A.2.2) and populated a custom-designed screening form to document the screening decisions. The topic area subject matter experts performed quality control on a randomly selected 33% of article references; of those, the screening decision has been revised in approximately 15% of cases.

All additional screening was implemented outside of litstream™ using Excel workbooks. This occurred in the following circumstances:

- Search augmentation: We screened reference lists from the bibliographies of articles selected for the full text review. The screening guidelines have been identical to those used for litstream™;
- Identifying review articles: We screened potential review papers for Topic 4 (identified as described in section A.2.4). In this case, the screening guidance was extended to focus specifically on the review papers and note the regional scope of the review.[23]

Table 16 summarizes the manual screening process results.

Table 16. Results of the Title and Abstract Screening

Manually Screened Article Set Type	Number of Articles Screened	Number of Articles Promoted to Full Text Review Based on Title and Abstract Information (by Topic):						
		1-6	1	2	3	4	5	6
Seed articles	1,046	202	106	106	104	48	44	46
Pilot screening	36	19	5	7	10	10	5	3
litstream™ set	1,005	242	57	48	63	76	91	33
Reference list follow-up	–[a]	84	–[b]	–[b]	–[b]	84	–[b]	84
Potential review article set[c]	562	94[c]	–[b]	–[b]	–[b]	94[c]	–[b]	94[c]
Total	2,649	560	168	161	177	231	140	179

Notes:
[a] The number is not available because the screeners have not been tasked with counting all items in the reference lists of the articles undergoing full text review. [b] Task not implemented for topic area. [c] Some of the articles retrieved via this search were not review papers. As such, we promoted 68 review articles to the full text review; the remaining articles promoted to full text review were primary research work.

[22] 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).
[23] In that, the reviews have been tagged using one of the following mutually exclusive categories: global, focused on the US, focused on high-income countries, focused on low- or middle-income countries, or unclear without full text.

A.3.2. Gray Literature Screening

Gray literature search results have been manually screened outside litstream™. In that, we relied on the available meta-data, such as URL text, web-page title, etc., and focused on selecting articles whose meta-data contained only the most salient terms. For the emissions profiles and indoor air quality topics, we focused on topics not well covered by the reviewed peer-reviewed literature: for emissions profiles that was space heaters, fireplaces, gas stoves, gas clothes dryers, and gas water heaters, and for indoor air quality that was gas fireplaces, gas clothes dryers, gas water heaters, and methods of exhaust and ventilation. Furthermore, we focused only on subset of the most important gray literature sources due to the resource constraints. Table 17 contains the results of the gray literature screening, again presented under the original topic definitions. (See Table 12). Gray literature reviews for other topics that was not post-hoc were used only sparingly and as needed.

Table 17. Results of the Gray Literature Screening

Manually Screened Article Set	Number of Articles Screened	Number of Articles Promoted to Full Text Review Based on Article Meta-Information (by Topic):						
		1-6	1	2	3	4	5	6
Domains Searched for Topic 1[a]	188	188	–[b]	–[b]	–[b]	–[b]	–[b]	–[b]
Domains Searched for Topic 2-3[a]	3,943	40	–[b]	40	40	–[b]	–[b]	–[b]
CDC domain searched for Topic 4 & 6	470	27[c]	–[b]	–[b]	–[b]	27[c]	–[b]	27[c]

Notes:

[a] List of domains is available in Appendix B. [b] Task not implemented for topic area. [c] Some of the articles retrieved via this search were not gray literature, but rather peer reviewed publications.

A.4. Full Text Review and Information Extraction

We obtained full text for a subset of articles selected for the full text review (see statistics in Table 18). These materials have undergone manual information extraction aiming to further characterize its content. To this end, we have developed Excel workbooks with topic-specific full text extraction templates and engaged the screener team in populating them. Subject matter experts reviewed the extracted information to ensure quality.

Table 18. Number of Articles with Accessible Full Text

<table>
<tr><th rowspan="2">Manually Screened Article Set</th><th colspan="7">Number of References Relevant to Topic based on Meta-Information Screening:</th></tr>
<tr><th>1-6*</th><th>1</th><th>2</th><th>3</th><th>4</th><th>6</th><th>5</th></tr>
<tr><td>Articles promoted to full text review based on title and abstract screening</td><td>553</td><td>168</td><td>161</td><td>177</td><td colspan="2">224</td><td>140</td></tr>
<tr><td>Articles selected from gray literature sources (full text already accessible)</td><td>255</td><td>188</td><td colspan="2">40</td><td colspan="2">27</td><td>--</td></tr>
<tr><td>Articles added via post-hoc manual searches</td><td>42</td><td>5</td><td colspan="2">9</td><td colspan="2">23</td><td>5</td></tr>
<tr><td>Full text accessible for review</td><td>850</td><td>361</td><td>54</td><td>65</td><td colspan="2">239</td><td>145</td></tr>
</table>

Notes: * Due to the overlaps across topics, the number of references in topic-specific columns can be greater than the number of references listed in for topics 1-6 overall.

A.5. Other Resources Consulted

In addition to the literature obtained via searches, we consulted the following additional data sources to address several topic-specific questions:

- The National Emissions Inventory for 2017 (United States Environmental Protection Agency [EPA], 2017) 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 CAPs and precursor pollutants, along with a variety of hazardous air pollutants. Residential combustion are tracked in four fuel categories: Natural Gas, Oil, Wood, and Other. This database is used to inform Topic 5. 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 2017 NEI was released in April 2020. The NEI does not include GHG emissions.
- The U.S. EPA GHG Inventory (United States Environmental Protection Agency [EPA], 2022c) is prepared annually by the EPA. This includes the *Inventory of U.S. Greenhouse Gas Emissions and Sinks* published since the early 1990s and the newer *Inventory of U.S. Greenhouse Gas Emissions and Sinks by State*. Provides a comprehensive accounting of the six primary greenhouse gas emissions for all man-made sources nationally. It does not include black carbon particulate (black carbon). It does include total residential sector GHG emissions. This inventory national greenhouse gas inventory is submitted to the United Nations.
    - EPA's AP-42 (United States Environmental Protection Agency [EPA], 2022a) is a national compendium of emission factors, published by EPA since the 1970s.

- The U.S. Energy Information Administration's (EIA) Residential Energy Consumption Survey (United States Energy Information Administration [EIA], 2015, 2020) is produced every four years. The most recent complete information is from the 2015 version, although the 2020 report became available in May of 2022. First conducted in 1978, RECS is based on a nationally representative sample of housing units. It is a compilation of information on housing unit, usage patterns, and household demographics combined with data from energy suppliers to these homes to estimate energy costs and usage for heating, cooling, appliances and other end uses. It is the foundation of EIA's Annual Energy Outlook (AEO).
- The best resources for the quantities of existing products and quantities of products shipped are the manufacturers and the associated trade associations. Any biases reflected in these reports are clearly founded by the purposes of those organizations. The information is weighted on both sides as to the number of reported units shipped as well as lack of reporting information due to trade competition.

A.6. Search Strings

Table 12 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. 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. Because EBSCO databases do not include MeSH terms, where appropriate, equivalent terms were used in EBSCO search sets. Hence, the combination of terms within each search set differed slightly for each database platform.

All queries run in PubMed and EBSCO used filters to restrict results to English-language materials published from 2000 to 2022. EBSCO queries were additionally limited to academic publication and document types and to the E-Journals, Environment Complete, Energy & Power Source, and Academic Source Ultimate databases. PubMed queries using the "Review Study" search set also employed PubMed filters to restrict references to Reviews, Systematic Reviews, or Meta-Analyses.

Table 18 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. Refer to Table 12 for the exact combination of search sets comprising all queries run.

Table 19. 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 organic compound"[TIAB] OR "volatile organic compounds"[TIAB])))	((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
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]) 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 ((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] 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])	("duct cleaning" OR "energy efficiency" OR "exposure reduction" OR "filter replacement" OR "moisture control" OR "range hood" OR "range hoods" OR ventilation 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")))

Search Set	PubMed Search Syntax	EBSCO Search Syntax
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])	(disease* OR "Health" OR illness* OR "Morbidity" OR "Disability Adjusted Life Year" OR "Disability Adjusted Life Years")
Indoor Air Quality	("Air Pollution, Indoor"[MeSH] OR (indoor*[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 organic compound"[TIAB] OR "volatile organic compounds"[TIAB])))	(indoor* AND ("air quality" OR "black carbon" OR "carbon dioxide" OR "carbon dioxides" OR "carbon monoxide" OR "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"))
Modeling	("burden"[TIAB] OR quantif*[TIAB] OR evaluat*[TIAB] OR assess*[TIAB] OR estimat*[TIAB] OR impact*[TIAB] OR simulat*[TIAB] OR "reduction"[TIAB] OR model*[TIAB] OR intervention*[TIAB] OR "policy"[TIAB] OR "attribution"[TIAB] OR "atrributable"[TIAB] OR "contribution"[TIAB])	(models OR modeling OR modelling)
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")

Search Set	PubMed Search Syntax	EBSCO Search Syntax
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 "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]))	(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))
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])	("Home" OR "Homes" OR "House" OR "Houses" OR "Housing" OR household* OR Indoor* OR "Residential")

A.7. 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 and whether articles had a focus that did not include the United States, were review articles, or were non-English studies.

Exclusion criteria included the following:

- Not written in English,
- Published before 2000,
- 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 indoor residential combustion 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.7.1. **Topic 1. Indoor Combustion Technologies**

Identifies a (combustion-based) technology(ies), appliance(s), and/or fuel(s) in use in U.S. homes.

- Can differentiate between more than one technology in use for appliances or identify the relative prevalence of each in U.S. homes.
- "Technologies" include fuels, appliances (e.g., fireplaces or heating), or controls (e.g., vent hoods or indoor air filters).
- "Prevalence" can refer to frequency of use within a home, or frequencies of use across different homes. May also include prevalence of reduction technologies (e.g., venting) in U.S. homes.

A.7.2. Topic 2. Emissions Profiles

Numerically quantifies the *emissions* of air pollutants (e.g., CAPs, HAPs, and GHGs) from appliances designed for or installed or operated in U.S. homes.

- Can consider whether there is a difference in how appliances are designed/engineered to emit and how they emit during actual operation (e.g., can include if it was installed in a noncertified way that bypasses controls).
- Can consider whether there are quantified differences in emissions between different fuels of a similar appliance type (such as natural gas versus propane).
- "Air toxics" are toxic contaminants. There is a long list. PAH or POM are the most likely to be mentioned, along with ultrafine particles, formaldehyde, and acetaldehyde. Additional resources on air pollutants found can be consulted.
- "Criteria pollutants" are:
    - particulate matter 2.5 microns or less ($PM_{2.5}$)
    - volatile organic compounds (VOCs)
    - carbon monoxide (CO)
    - sulfur dioxide (SO_2)
    - nitrogen oxides (NO_x)
- "GHGs" include:

- CO_2
- CH_4/methane – particularly important, including from natural gas leaks
- N_2O/nitrous oxide

- “Emissions” are not to be confused with “concentrations”. Emissions are typically in units of mass/time (e.g., ng/min) or possibly mass/mass (e.g., g/kg) and they describe what is leaving the appliance.
- Limited to “primary” emissions, meaning, secondary pollutant formation, like using a gas stove to cook food and reporting resulting PM emissions originating from the food, not the appliance itself are beyond the scope. Mold or mildew resulting from water formation as a byproduct of combustion are also beyond the scope.

A.7.3. **Topic 3. Contributions to Indoor Air Quality**

Quantifies the indoor air concentrations of air pollutants (e.g., CAPs, HAPs, and GHGs) emitted from the appliances and attributable to appliance used in U.S. homes.

- Can include the effects of intervention to reduce indoor concentrations, such as vent hoods, filters used indoors, or combustion controls, or the impact of the built environment (e.g., building ventilation rate.)
- Can be modeling studies that quantify the health burden of combustion-related indoor air pollution or health benefits/impacts of reducing this pollution via controls
- Can discuss indoor air pollution from multiple sources but must include the impact attributable specifically to sources of indoor residential combustion. For example, indoor VOC concentrations are impacted by combustion and non-combustion sources; we are interested in papers that explore VOC health impacts attributable to combustion appliances which could be expressed as effect modification by source, particularly if there is source modeling.
- “Criteria pollutants”, “air toxics”, and “GHGs” are the same as defined for Topic 2.
- “Concentrations” are not to be confused with “emissions”. Concentrations are typically in units of mass/volume (e.g., $\mu g/m^3$, ppm) and they describe the amount of the pollutant in the air at some distance away from the appliance. For particulate matter, particle counts and sizes also apply here.
- “Attributable to the appliances” means the authors have deduced that the pollutant concentration came from the appliance, not from other sources (not from other non-combustion sources like electric items, furniture, etc.; not from outdoor sources).
- Limited to “primary” effects, meaning secondary effects, like using a gas stove to cook food and reporting resulting concentrations originating from the food, not the appliance itself are

beyond the scope. Mold or mildew resulting from water formation as a byproduct of combustion are also beyond the scope.

- "Intervention" can refer to housing type, housing ventilation, appliance venting/hoods, air filters, etc.
    - The impact on indoor air concentrations from control measures including ventilation systems (e.g., range hoods, bathroom fans), filtration systems (e.g., standalone air purifiers, MERV-rated HVAC filters), and measures to improve functioning of these systems (e.g., air duct cleaning).

A.7.4. **Topic 4. Health Impacts from Residential Exposure to Pollutants from Indoor Combustion Sources**

Adverse human health effects, indoors, from occupants' exposure to pollutants emitted from indoor residential combustion in U.S. homes.

- Would not include general exposure risks to pollutants unless there is an explicit link to indoor residential combustion.
- May apply to individual air pollutants measured indoors or mixtures of air pollutants, so long as directly result from indoor, residential combustion.
- Human health effects could include asthma incidence, asthma or allergy exacerbation, respiratory symptoms, cardiovascular symptoms, promotion of infectious disease (e.g., pneumonia, acute lower respiratory infections (ALRI), 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.
- Might include epidemiology studies on health impacts of indoor air quality associated with indoor residential combustion related to smoking, tobacco use, burning of incense or candles.
- 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.7.5. **Topic 5. Contributions to Outdoor Air Quality and Climate Change**

Contribution of the appliance's indoor emissions to outdoor air pollution (e.g., CAPs, HAPs, and GHGs)

- Includes effects on climate from indoor combustion.
- "Criteria pollutants", "air toxics", and "GHGs" are the same as defined for Topic 2.

- “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.7.6. **Topic 6. Exposures and Health Impacts from Ambient Exposure and Climate Change**

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. 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 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:

ALA_IRC sources and impacts_Appendix_B_All References.xlsx.

The workbook contains a ranked list of potentially relevant articles (based on automated screening process) retrieved from bibliographic databases and a collection of articles retrieved from prioritized gray literature sources. 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.

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