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Indoor Air Sources of Outdoor Air Pollution: Health Consequences, Policy, and Recommendations

An Official American Thoracic Society Workshop Report

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Abstract

Indoor sources of air pollution worsen indoor and outdoor air quality. Thus, identifying and reducing indoor pollutant sources would decrease both indoor and outdoor air pollution, benefit public health, and help address the climate crisis. As outdoor sources come under regulatory control, unregulated indoor sources become a rising percentage of the problem. This American Thoracic Society workshop was convened in 2022 to evaluate this increasing proportion of indoor contributions to outdoor air quality. The workshop was conducted by physicians and scientists, including atmospheric and aerosol scientists, environmental engineers, toxicologists, epidemiologists, regulatory policy experts, and pediatric and adult pulmonologists. Presentations and discussion sessions were centered on *1*) the generation and migration of pollutants from indoors to outdoors, *2*) the sources and circumstances representing the greatest threat, and *3*) effective remedies to reduce the health burden of indoor sources of air pollution. The scope of the workshop was residential and commercial sources of indoor air pollution in the United States. Topics included wood burning, natural gas, cooking, evaporative volatile organic compounds, source apportionment, and regulatory policy. The workshop concluded that indoor sources of air pollution are significant contributors to outdoor air quality and that source control and filtration are the most effective measures to reduce indoor contributions to outdoor air. Interventions should prioritize environmental justice: Households of lower socioeconomic status have higher concentrations of indoor air pollutants from both indoor and outdoor sources. We identify research priorities, potential health benefits, and mitigation actions to consider (e.g., switching from natural gas to electric stoves and transitioning to scent-free consumer products). The workshop committee emphasizes the benefits of combustion-free homes and businesses and recommends economic, legislative, and education strategies aimed at achieving this goal.

Keywords: indoor air pollution; wood burning; natural gas; cooking; volatile organic compounds

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Introduction

People spend more than 80% of their time indoors where they are exposed to air pollutants, many of which are also found outdoors (1). The predominant global source of outdoor pollution is fossil fuel burning. Indoor sources of air pollution are less well characterized, yet there is growing recognition of the importance of indoor air quality for human health, especially as outdoor sources come under control (2). Outdoor air pollutants are subject to regulation under the Clean Air Act in the United States, but no similar regulation exists for the concentrations of the same pollutants in the indoor environment. However, modulating indoor pollutant sources can reduce both indoor exposures and their contributions to outdoor pollutant concentrations, which are subject to the Clean Air Act, and thus improve public health in both environments.

This 2022 workshop, titled “Health Consequences and the Relative Contribution of Indoor versus Outdoor Pollutants,” addressed three charge questions: *1*) What is the current state of knowledge regarding the generation and migration of pollutants from indoors to outdoors? *2*) What sources and circumstances are the greatest threat and the most actionable? *3*) Given what we know about the generation and migration of pollutants from indoors to outdoors and climate change, what remedies may be effective in reducing the health burden of air pollution? Our scope was limited to residential and commercial sources of indoor air pollution in the United States.

The workshop was conducted by physicians and scientists with expertise in the health effects of air pollution and included atmospheric and aerosol scientists, environmental engineers, toxicologists, epidemiologists, regulatory policy experts, and pediatric and adult pulmonologists. The 22 participants completed six presentation and discussion sessions, concluding with future needs and priorities. The six topics were wood burning, natural gas, cooking, evaporative volatile organic compounds (VOCs), source apportionment, and regulatory policy. Recommendations for action are reported.

Wood Burning

Wood accounts for the main heating fuel in only 2% of U.S. households but produces more than 90% of fine particulate matter (PM; $\leq$2.5 μm in aerodynamic diameter [$PM_{2.5}$]) emissions from the residential heating sector and 22% of the overall primary emissions of $PM_{2.5}$ (3–5). Between 2 and 3 million U.S. homes use wood burning appliances as the primary source of heat; another 8 million use wood as a secondary heating source (6, 7). In areas with higher concentrations of homes with wood burning appliances, including communities where electricity access is limited or alternative heating strategies are cost prohibitive, indoor wood burning appliances can represent the dominant source of ambient air pollution in winter. These conditions occur disproportionately in rural areas and in U.S. households with incomes below the poverty line (3, 8). Recreational wood burning can also contribute to increases in both indoor and outdoor PM concentrations (9, 10). Initiatives resulting from community, academic, and governmental partnerships have demonstrated the impact of residential wood burning on outdoor air pollution while providing a framework and impetus for evidence-based interventions (11).

The composition of wood burning-generated PM differs from that of fossil fuel–generated PM, and their health impacts per unit (micrograms per cubic meter) have been shown to differ (12, 13). Wood smoke contains a complex mixture of pollutants, including $PM_{2.5}$; ultrafine particles; carbon monoxide (CO); carbon dioxide (CO_2); nitrogen oxide (NO_x); CH_4, or methane; VOCs; and polyaromatic hydrocarbons (PAHs), some of which also contribute to secondary pollutant formation, such as ground-level ozone. The levels and relative contributions of these wood smoke components depend on widely variable factors, including appliance type, venting, efficiency and maintenance, and fuel type, many of which are modifiable (14). Venting efficiency and performance may be optimized with proper operation and maintenance to reduce emissions. Type, size, and wood product quality (e.g., avoiding paint and other treatments) also influence efficiency and pollutant release. Smaller cordwood pieces, lower moisture content ($<$20% moisture content, which can be achieved by drying wood for at least 6 months, is recommended), and fire quality optimization can reduce incomplete combustion (e.g., smoldering) (15, 16). Pellet-burning appliances are generally desirable, although research on pellet stove emissions and health effects is limited (17).

Interventions to Prevent Health Effects Related to Wood Burning

Multiple national and local interventions focus on mitigating the harmful effects of wood burning pollution, including U.S. Environmental Protection Agency (EPA) emission standards and certification updates and education campaigns involving partnerships between industry, community, government, and academia. Wood stove exchange programs and change-out programs, in particular, have shown promise as impactful interventions, with reductions in ambient $PM_{2.5}$ and fewer days exceeding the 24-hour National Ambient Air Quality Standards for $PM_{2.5}$ of 35 $\mu g/m^3$ (Table 1) (11). In addition to health benefits from reduced pollution, interventions that switch out older, less efficient appliances with newer, energy-efficient appliances may have

Table 1. Case study related to wood burning that may serve as a model for other indoor sources of pollution that impact both indoor and outdoor air

Libby, Montana, is located in a mountain valley susceptible to frequent inversion layers in the winter months. Before 2006, Libby was one of four nonattainment areas for the U.S. Environmental Protection Agency $PM_{2.5}$ (particulate matter with an aerodynamic diameter $\leqslant 2.5$ μm) National Ambient Air Quality Standards (1997 standard). In an example of partnership among an academic university, local government, and the community, researchers from the University of Montana used chemical mass balance modeling to reveal that residential wood burning contributed to an average of 82% of measured ambient $PM_{2.5}$ during the winter months (136). Between 2005 and 2007, in one of the nation's largest change-outs, over 1,100 wood stoves were exchanged, rebuilt, or disabled, resulting in a significant (20%) reduction in ambient $PM_{2.5}$ levels from 27.0 μg/m^3 (SD = 12.5) to 21.8 μg/m^3 (SD = 4.9). In a subset of homes where indoor $PM_{2.5}$ was measured, average $PM_{2.5}$ concentrations were reduced 71% (137). In a follow-up study that included 3 additional years after change-outs, indoor $PM_{2.5}$ decreased from 45.0 μg/m^3 (SD = 33.0) to 18.0 μg/m^3 (SD = 14.5), and ambient $PM_{2.5}$ decreased from 25.3 μg/m^3 (SD = 12.4) to 17.7 μg/m^3 (SD = 6.85) (138). These investigations focused on $PM_{2.5}$ concentration; however, $PM_{2.5}$ composition and other pollutants that are highly, but variably, correlated with wood burning conditions have not been systematically investigated.

Definition of abbreviation: SD = standard deviation.

long-term cost savings that offset the upfront costs of switching, although wood stoves tend to be cheaper for heating than electric furnaces (8, 18). Federal and state programs exist to offset the costs of replacing or improving the efficiency of wood stoves, including government–private sector partnerships, vouchers, and tax credits, many of which include additional financial support for low-income households (19, 20).

Natural Gas

Natural gas is the primary residential fuel type for heating and is commonly used for residential, industrial, and commercial electricity generation (21). Oil burning is also used for heating, but to a far lesser extent (4.6% of homes use heating oil, compared with 60.4% using natural gas) (6). The production, distribution, and utilization of natural gas are all sources of primary and secondary air pollutants (Table 2). The natural gas distribution system for residential and commercial buildings is an important source of fugitive greenhouse gas emissions, specifically, methane, the predominant constituent of natural gas (22). Leaks can occur throughout the system, including at the interface with individual devices, contributing to global warming (23). In U.S. urban centers, areas with higher percentages of people of color, older homes, and lower incomes have been found to have a higher density of natural gas leaks (24). A recent study quantified methane released in 53 homes during all phases of stove use: More than 75% of methane emissions occurred when the stoves were turned off (25). These investigators estimated that annual methane emission from gas stoves in U.S. homes have a climate change–forcing impact equivalent to the annual methane emissions of 500,000 cars. In the indoor environment, natural gas is also used for cooking and is well known to affect indoor air quality (26). The available evidence about emissions from natural gas appliances (e.g., furnaces, water heaters) used in residential and commercial conditions comes from experiments under carefully controlled conditions, likely leading to underestimates of true pollutant emissions from natural gas appliances in real-world residential and commercial settings (27).

The exhaust from residential and commercial natural gas combustion is often vented directly outdoors, contributing to outdoor air pollution. Natural gas combustion is designed to convert its main chemical elements—hydrogen and carbon—to their lowest energy forms, water and CO_2. Pollutants are formed through three main channels: *1*) through N_2 conversion in combustion air to NO_x, *2*) as a result of fuel impurities (e.g., toxic metals), and *3*) as products of incomplete combustion (28). Products of incomplete natural gas combustion include PAH, formaldehyde, CO, and ultrafine particles (29). Emission rates are sensitive to combustion conditions. A burner with an improper mix of air and fuel emits considerably more products of incomplete combustion than a well-tuned burner. The quantity of pollutants emitted by natural gas combustion scales approximately with the quantity of fuel burned. Emissions of CO_2 and NO_x from natural gas combustion in buildings are largely determined by the amount of space heating and hot water production, as these represent the dominant fuel usage. NO_x emissions and their secondary products contribute to the atmospheric abundance of criteria air pollutants: NO_2, ozone, and $PM_{2.5}$ (30). According to a recent estimate by the California Air Resources Board, approximately 5% of California's NO_x emissions are from natural gas combustion in buildings (31).

In a related example, gasoline-powered automobiles—"super-emitters" (vehicles with inefficient, often older engines)—are responsible for a disproportionate share of cumulative emissions from the vehicle fleet (32). It is unknown whether super-emitter residential or commercial furnaces and other combustion appliances disproportionately pollute outdoor air with products of incomplete combustion.

Table 2. Products of natural gas combustion

Complete combustion	Incomplete combustion	Additional emissions
NO_x	Polycyclic aromatic hydrocarbons	Nitrous acid (HONO)
CO_2	Formaldehyde	Metals
SO_x	Ultrafine particles (soot), carbon monoxide	Methane (leakage)

Definition of abbreviations: CO_2 = carbon dioxide; NO_x = nitrous oxide; SO_x = sulfur oxides.

Interventions to Prevent Health Effects Related to Natural Gas Burning

Actions to reduce outdoor air pollution from residential and commercial use of natural gas can be clustered in two major categories: reducing emissions from existing infrastructure and limiting new development and installations. A list of potential actions to update, replace, or prevent natural gas combustion appliances in residential and commercial buildings is shown in Figure 1.

There is a need for high-quality field data that characterize emission factors from new and aging furnaces and other appliances currently in widespread use. By sampling residential and commercial properties, both the central tendency of emission factors and the relative presence of super-emitters could be characterized and prioritized for repair or replacement. Incentivizing the use of efficient electric appliances (e.g., heat pumps) and clean energy sources may be effective nonregulatory options to promote the replacement of existing residential and commercial natural gas appliances (33).

New appliances and the construction of new buildings present opportunities to reduce natural gas use. Legislation can be used to prohibit or phase out new natural gas distribution systems and prevent new natural gas appliance installation or connections to homes and commercial buildings (34–36). Nonregulatory options include voluntary industry standards and new development of high-efficiency and electric appliances. Phasing out natural gas for heating and cooking will not only improve respiratory health by improving indoor and outdoor air quality through the reduction of hazardous by-products and secondary pollutants such as ozone but also will mitigate climate change impacts by reducing leaks of greenhouse gases (25).

Cooking

Residential and commercial cooking are major sources of indoor air pollution that also contribute to outdoor air pollution. Globally, household cooking with solid fuels is a strong contributor to outdoor air pollution (37), but the present discussion focuses on residential cooking in high-income countries. The majority of cooking appliances in the United States use electricity or natural gas (38).

Cooking-related emissions vary with the type of energy used. Natural gas combustion produces NO_x and some other air pollutants that cooking with electricity does not produce. Homes that use gas cooking, even with stove venting, often exceed outdoor levels of NO_2 (29). Both electric and gas cooking produce PM and ultrafine particles, but their nature and abundance depend on multiple factors, including cooking method (e.g., frying versus wet cooking), pan size (smaller pans are better), oil (the best type depends on smoking temperature), cooking temperature, food type and additives, heating source surface area (smaller burners are better), and ventilation (39, 40). Gas combustion and electrical heating generally emit smaller particles, whereas the food itself produces larger particles (41). Studies have found that emissions of ultrafine particles (<100 nm) were 40 times lower on induction cooktops compared with cooktops using either gas or resistance electricity (42, 43).

The nature and potential health impacts of indoor air pollution from cooking differ considerably from the impacts of outdoor air pollution. Peak indoor $PM_{2.5}$ and NO_2 concentrations generated by cooking may be higher than those outdoors, often exceeding ambient health-based air quality standards (25, 27), albeit for short time periods. NO_x

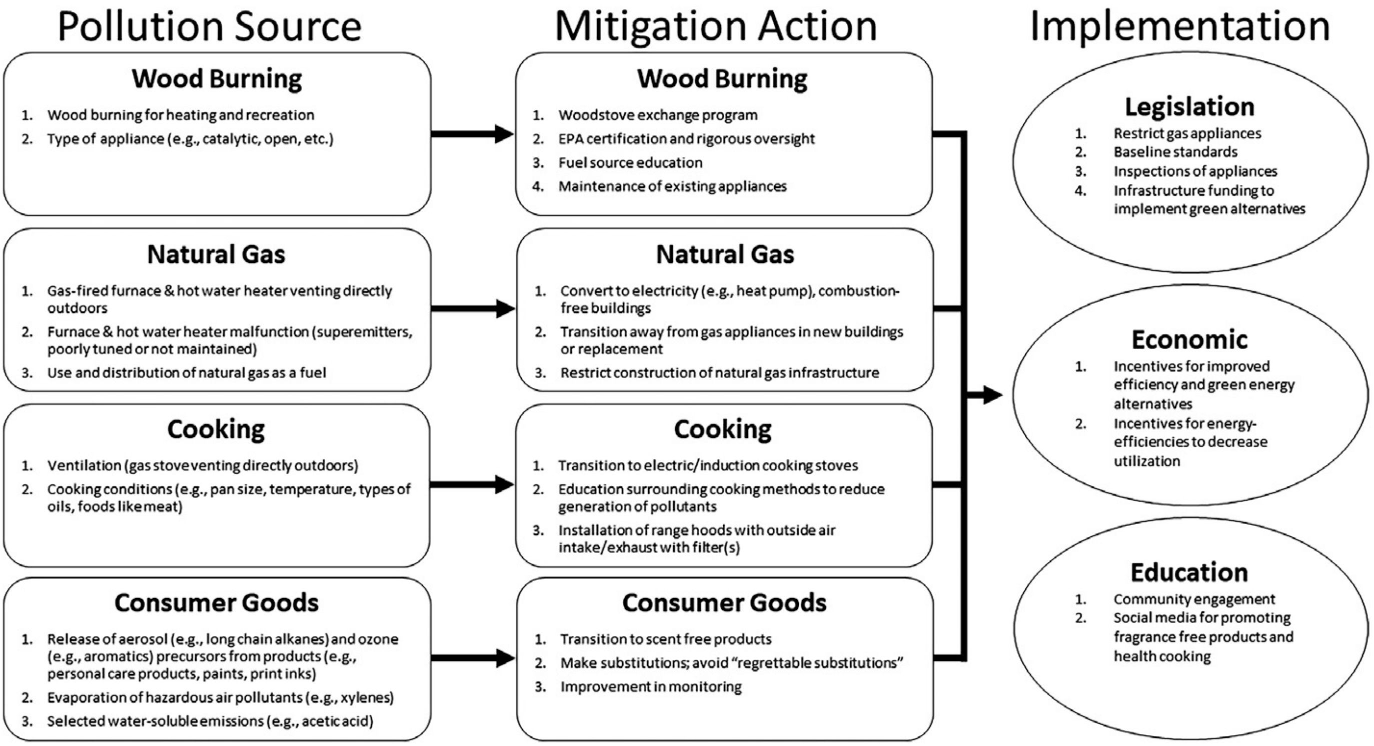

Figure 1. Potential targets and actions to reduce contributions of indoor air pollutants to outdoors from residential and commercial sources. EPA = Environmental Protection Agency.

emissions are linearly related to the amount of natural gas burned (25). Cooking also produces ultrafine particles (44). However, the contribution of residential cooking to the health effects of outdoor ultrafine particles is not known. $PM_{2.5}$ resulting from residential cooking and heating combined have been estimated to result in 7,550 to 10,850 deaths per year in the United States (45).

There are also significant emissions from cooking in commercial buildings, including restaurants and various institutions (schools, universities, hospitals, prisons, food kitchens, etc.), which cook much larger quantities of food. Concentrations of organic aerosol, a constituent of $PM_{2.5}$, measured with an aerosol mass spectrometer mounted on a mobile laboratory, were found to be greatly elevated in the vicinity of restaurants and commercial districts containing multiple restaurants (46). Other studies have also shown that restaurants contribute to particulate air pollution (47, 48), particularly restaurants that feature grilled food compared with other types of cooking (49). $PM_{2.5}$ from commercial cooking and food processing has been estimated to result in 2,730 to 5,300 deaths per year (45). High-resolution air pollution networks can likely play a role in identifying super-emitters and may also offer a potential way to quantify the impact of cooking in commercial cooking in buildings such as restaurants (50).

Interventions to Prevent Health Effects Related to Commercial and Residential Cooking

Emissions from commercial cooking have begun to attract regulatory attention. For example, in 2016, New York City amended its Air Pollution Control Code to include “cookstoves” as any wood-fired or anthracite coal–fired appliance used primarily for cooking food for onsite consumption at a food service establishment (51). They prohibited the installation of new cookstoves for the preparation of food intended for onsite consumption or retail purchase without the use of an emission control device for odors, smoke, and PM. California’s San Joaquin Valley Air Quality Management District adopted a comprehensive strategy to address emissions from commercial underfired charbroilers, such as requiring catalytic oxidizers for charbroilers, including those used in many fast-food restaurants. Since initial rule adoption, $PM_{2.5}$ emissions from charbroilers have been reduced by 84% (52).

Range hoods are commonly installed in home kitchens to vent PM and gas emissions and thereby reduce exposure to occupants. However, whereas some hoods vent outside the building, others filter particles and return the gaseous pollutants indoors. Range hood use depends on individual choice; operational noise may limit its use. Self-reporting typically overestimates actual use (53). Range hoods can reduce indoor $PM_{2.5}$, NO_x, and CO from gas ranges and $PM_{2.5}$ from electric stoves, but hoods vary widely in capture efficiency. Most capture emissions from back burners better than front burners (54). Home mechanical ventilation and filtration with either a central ventilation system with a good quality filter (e.g., minimum efficiency reporting value, or MERV, of 13) or a portable high-efficiency particulate-absorbing, or HEPA, filtration device can help reduce both indoor pollutant concentrations and the transport of cooking-generated particles outdoors (55). HEPA filters have been shown to reduce indoor air pollution and aeroallergens with associated improvements in asthma symptoms and lung function, although further intervention studies are warranted (56–58).

There may be health cobenefits to switching to electric cooking, as previously described (41, 42, 59). Quantitative estimates of the potential health benefits of this approach are needed. Public education to combat the myth that cooking with gas is superior to electricity may modify cooking behavior. Electric induction stoves, which are three times more efficient than gas (60), are a good alternative, perhaps closer to or even exceeding the performance of gas cooking, in contrast to heated-coil burners (61). Induction stoves may be more expensive, although subsidies to incentivize the change-over are expected to be implemented with the Inflation Reduction Act of 2022 (62). Finally, the source of electricity for cooking is important, as clean renewable sources will decrease outdoor air pollution from fossil fuel combustion.

Evaporative VOCs

VOCs are prevalent indoors and can be either directly emitted by consumer products, wood burning, cooking, and natural gas combustion or formed from secondary chemistry in the air. Some VOCs are semivolatile or water soluble (e.g., acetic acid, glyoxal, epoxides, peroxides) with implications for their fate and potential to form secondary criteria pollutants. Because of proximity and confinement, indoor inhalation of VOCs emitted indoors is a few orders of magnitude larger than inhalation of the same compound once it has been transported outdoors. In ambient air, indoor sources of VOCs can lead to secondary products such as ozone and $PM_{2.5}$ or be recognized as hazardous air pollutants (HAPs). Consumer goods, such as personal care products and paints, are one source known to release precursors to $PM_{2.5}$ (specifically, precursors to secondary organic aerosol [SOA], a major component of $PM_{2.5}$) such as terpenes and precursors to ozone such as small alcohols, glyoxal, and glycolic acid (63). Racially and ethnically minoritized persons are at disproportionate risk of being exposed to VOCs (64, 65).

The major driver of secondary chemistry in indoor air is ozone, and the major source of indoor ozone is outdoor air (66). Indoor sources, when they occur, include devices such as electrostatic precipitators, photocopiers, laser printers, and ionizing air cleaners. Of recent concern are germicidal ultraviolet lights operating at 222 nm, which can emit substantial amounts of ozone (67). The magnitude of oxidized VOCs resulting from ozone-initiated chemistry in indoor air (68) and on indoor surfaces (69, 70) is substantial. Such secondary emissions should be added to the list of VOCs from indoor sources that potentially affect outdoor air. A prime example is 6-methyl-5-heptene-2-one, produced from the reaction of skin oils with ozone, which significantly impacts the lifetime and, ultimately, the concentration of hydroxyl radicals in the air (71–73).

One evolving area of research is evaluating the toxicity of and exposure to chemicals in consumer products (e.g., the EPA’s ToxCast) (74–76), although the understanding of health impacts of VOCs derived from chemical processes, rather than directly emitted from consumer products, is limited (77–79).

The VOCs with the greatest potential to influence SOA formation outdoors include those of intermediate and lower volatility (e.g., alkanes with 15 or more carbon atoms, abundant in printing inks and petroleum-based products) and those with double bonds (alkenes, especially monoterpenes, which are ubiquitous in fragrances) (80, 81). Major VOC sources include scented consumer products (e.g., personal care products, cleaning agents, laundry soap, dryer sheets). Some cleaning products use terpenes and terpene alcohols as solvents as well as for scent. In the United States and Europe, there are high exposures to scented products (82, 83), including air fresheners, which are associated with adverse health effects (84). Whereas some products depend on the volatility of active agents at room temperature, others (e.g., plug-in devices and scented candles) deliberately increase volatility through heating. Unscented sorbents, designed to trap odorous compounds, are not included in this group. There is a need for further research—for instance, field studies that deploy instrumentation capable of detecting trace VOC compounds—to provide insight to the seasonal changes, diurnal patterns, and areas affected and, ultimately, to human respiratory disease consequences.

More than 350,000 chemicals are currently used in consumer products. Many constituents are not publicly identified, either because they are considered proprietary (>50,000) or because they are poorly described (up to 70,000) (77). Better understanding of the current mix and concentration of indoor air VOCs and their health effects would benefit from an updated large-scale survey in residences across the United States—something analogous to the Health Effects Institute–funded Relationships of Indoor, Outdoor, and Personal Air study that collected and analyzed the VOC composition in samples from more than 300 homes between 1999 and 2001 (85).

Interventions to Prevent Health Effects Related to VOCs

To some extent, we know that attitudes and behaviors can change over time: Smoking is a good example. With regard to VOC-emitting products, public settings are increasingly fragrance-free for health reasons (82). Fragrance compounds themselves may have health impacts, but fragrance compounds are generally only half the fragrance mass, with the rest being solvents and plasticizers such as diethyl phthalate, which is a known irritant (86). Thus, eliminating fragrances reduces the need for carrier species in products that could have other health impacts. Campaigns have been successful in advocating for schools changing to less harmful disinfectants and banning body sprays on the basis of concerns that students with asthma can be adversely impacted. Lower VOC-emitting personal care products and cleaning agents with reduced scented compounds are increasingly available in response to public concern about potential health effects. Collaborating with social media influencers on healthy beauty products may offer an opportunity to educate and energize youths who appear invested in climate change. The public can also work with industry to develop policies to reduce indoor emissions (e.g., product sources, sensors, publicly available data).

There is a paucity of health information to inform regulation of indoor VOCs, which is complicated by the large number of chemicals in use and the wide variability in chemical properties that govern their fate and transport. A subset of emitted VOCs are HAPs, which have existing regulation in the ambient air. Indoor sources, such as consumer products that emit VOCs, are already influenced by Clean Air Act regulation. For example, substituting compounds that are exempt from VOC regulation (40 CFR 51.100(s)) in product formulations results in lower ozone formation and can enable states to better meet the National Ambient Air Quality Standards for ozone. When it comes to regulating formulations, “regrettable substitutions”—where industry may choose to replace a banned additive with a distinct yet similar additive of unknown health effects, rather than using properly evaluated constituents—should be avoided (87).

Source Apportionment

Source apportionment techniques can be used to quantify the origins of air pollutants. The composition of ambient air pollutants in the United States is changing as sources such as vehicular and industrial emissions become more controlled, making indoor sources a larger fraction of the total. Products such as deodorants, paints, and cleaners, many of which are present indoors, are a source of evaporated VOCs and are growing in relative importance (88, 89). Coggon and colleagues showed that product usage emissions are ubiquitous in urban regions (90). Detailed modeling has shown that these product emissions are important contributors to ambient ozone and PM formation (81) that can account for half of the urban organic PM mass in summer (80). In addition to chemical products, cooking and residential wood burning remain major prevalent sources (as discussed in later sections). Reducing anthropogenic VOC emissions can lead to ambient air pollution–associated mortality reductions by lowering both SOA and ozone (91).

Some product sources can be identified through their chemical fingerprint (90, 92), but many indoor sources lack unique signatures in ambient air because of overlap with emissions from outdoor sources. For example, levoglucosan is a tracer for biomass burning (93) that has been used to identify the role of residential wood burning in locations like Rochester, New York (94). However, levoglucosan is also generated by wildland fires preventing differentiation of $PM_{2.5}$ from these sources if both are present. Indoor sources are also highly variable in location, and time and emissions are subject to reactive chemistry in the ambient atmosphere, further obscuring their signal.

Current routine air-monitoring networks lack the type of data, such as for individual particulate organic species, that could be used to identify specific contributions of indoor emissions to outdoor air (95). Lump and briquette coal combustion can be distinguished through the emission of primary sulfate and humic-like substances during the lower temperature phases of the burn cycle, although this would still not distinguish between material vented from indoors and fugitive emissions from indoors (96, 97). Supplementation of existing routine network data (e.g., through the EPA Chemical Speciation Network) with additional chemical speciation (either classes of organic aerosol or specific compounds) is needed to enable source- and composition-specific $PM_{2.5}$ health effects evaluations.

Given the close coupling between individual preferences and indoor air pollution sources, identifying the differential toxicity of indoor and outdoor sources is of high priority to communicate risk to the public. Differential toxicity is generally not established for ambient pollution sources (98), and even less so for indoor sources. However, there is information on certain species. For example, PAH and oxidants or oxidant-generating species are potentially long-term carcinogens (99). Hence, indoor combustion generating higher concentrations of PAH-containing particles could be an important mediator of health effects. Currently, there are insufficient data to build exposure-response functions for individual indoor sources. One way to handle exposure mixtures is using source-specific $PM_{2.5}$ estimates as the exposure metric (100–102).

Controlling sources has different potential for impacts at individual and population levels. Wood smoke and cooking emissions are recognized sources leading to high indoor air pollution levels (see previous sections). Mitigating them would have cobenefits for indoor and outdoor exposure on both individual and population levels. Chemical products are important in ozone and SOA formation, contributing almost 10% of annual average $PM_{2.5}$ and 9% of ozone in the contiguous United States (81). To reduce the ozone impacts of chemical products, ozone-reactive compounds should be replaced by species with a lower potential to form SOA. Furthermore, during episodes of high ozone when the potential for indoor production of fine PM through SOA is higher, residents could decrease their high-emitting activities. For instance, voluntary burn bans, when feasible, should be considered when temperature inversions are predicted to avoid high PM concentrations under the inversion layer.

Although fossil fuel combustion for heating is declining, future air conditioner (AC) use is expected to become more prevalent (21). More AC use will increase indoor losses of PM and oxygenated (water-soluble) VOCs (e.g., formaldehyde, acetic acid, formic acid) (103). However, building emissions (e.g., acetic and formic acid and furfural from wood in non–air-conditioned spaces) will also increase with temperature (104–106). Increased wildfire emissions will lead to more closed windows and, therefore, more AC and filter use (107, 108). These changes will have direct implications for emissions and for indoor chemistry, including the removal of some species through AC condensate (109). The benefits of AC use on indoor pollution characteristics will need to be weighed against emissions (particularly greenhouse gases and precursors of ozone and $PM_{2.5}$) resulting from increased electricity demand. As AC use becomes more prevalent with climate change and rising temperatures, those increases in AC use will be more prevalent in communities or households that can afford them (both from a purchase and energy cost perspective) (110). Federal government and state programs offer rebates for AC units for low-income households, yet there remain many vulnerable households without AC units that may be disproportionately exposed to higher temperatures and the power plant air pollution emissions generated as a result of the increased AC use (111). The relative contributions of different sources are expected to evolve with climate change, because of individual behavior changes and large-scale changes in fuel for heating and other home activities.

Regulatory Policies

For decades, the Clean Air Act has improved outdoor air quality, but outdoor air pollution continues to have measurable adverse health effects below current ambient standards (112). The Clean Air Act requires that the EPA set health-based ambient air quality standards with specific allowable concentrations for six criteria air pollutants (lead, PM, ozone, SO_2, NO_2, and CO). Another 188 named HAPs (113) or air toxics (e.g., formaldehyde, PAH, benzene, acrolein) are regulated by source control practices without specific allowable numerical concentrations, in the context of the requirement to “provide an ample margin of safety to protect public health” (114). Nine pollutants are identified as priority hazards on the basis of the robustness of the measured concentration data and the fraction of residences that appear to be impacted: Acetaldehyde, acrolein, benzene, 1,3-butadiene, 1,4-dichlorobenzene, formaldehyde, naphthalene, nitrogen dioxide, and $PM_{2.5}$ were identified as particularly hazardous for human health based on the basis of current measurements of indoor concentrations in a large number of houses (115). Numerous measurements of formaldehyde show indoor concentrations that are substantially higher than typical outdoor levels (116). However, indoor air quality is outside the regulatory scope of the Clean Air Act despite indoor air comprising most individual exposure. This results in the paradox that the majority of an individual’s daily inhaled PM and HAPs could be derived from indoor inhalation exposures.

Pollutants in indoor air are introduced from outdoors through open windows; heating, ventilation, and AC air intakes; and leaky building envelopes. Pollutants are also emitted directly into indoor air from indoor sources (e.g., cooking, consumer products). Furthermore, and of increasing importance, contaminants that are generated indoors contribute to outdoor air pollution (81, 89, 90, 117) and are then subject to the regulations under the Clean Air Act. States and local jurisdictions have authority under the Clean Air Act for regulating indoor sources of air pollution (including wood burning appliances, gas furnaces, water heaters, stoves, and dryers) on the basis of their contribution to outdoor air pollution. At the federal level, although the EPA does not regulate indoor PM arising from wood and solid fuel combustion, it now regulates devices (e.g., stoves and heaters) that are used to burn the wood because of their contributions to outdoor air quality (118). In 2015, EPA clean air standards for residential wood heaters were updated by establishing allowable emissions from indoor wood-fired boilers, forced air furnaces, and single burn-rate wood stoves (118). The EPA has yet to exercise regulatory authority to create federal emissions standards for other types of home appliances that vent directly outdoors (e.g., gas furnaces, water heaters, stoves, and dryers). Local municipalities and states have implemented policies, such as the New York Clean Heat Program, to transition from fossil fuel heating sources to cleaner energy forms with documented reductions in outdoor air pollution, including $PM_{2.5}$, SO_2, and NO_2 (119).

Traditional mitigation methods to reduce indoor pollutants are source control (i.e., reduce or remove the pollutant), ventilation with cleaner outdoor air (although this may increase indoor-to-outdoor pollutant transfer), and air filtration, the latter associated in a modeling study with reduced mortality and economic benefits in three cities across the United States representing different climates, including a mild, dry climate (Los Angeles, California), a hot and humid climate (Houston, Texas), and variable seasons (Elizabeth, New Jersey) (120). Thus, to mitigate the indoor contribution to outdoor air, source control and filtration are anticipated to be the most effective measures to reduce the amounts of VOCs, PM, and other contaminants released to the outdoors from indoor environments (121, 122). Furthermore, increasing efforts to weatherize and seal homes and, in some cases, decrease ventilation to improve energy efficiency and save energy, is also an opportunity to improve filtration of incoming and outgoing air by filtering outside air intake and exhaust.

Nevertheless, filtration systems are only useful when properly maintained and operated. Some filtration products actually release VOCs (123), and oxidation-based air cleaners can create toxic by-products (124). To address indoor air quality, public health advocates should consider expanding building codes (125), which have a tremendous impact on building efficiency, to address indoor air pollution. Decades of public health efforts have worked to reduce tobacco use and are now addressing electronic cigarette use (vaping), both of which can generate $PM_{2.5}$ indoors (126, 127). Regulatory policies should be informed by the adverse health effects associated with indoor sources of air pollution. Further research is needed, especially on the health effects related to the interplay between the social determinants of health, PM, smoking, VOCs, and allergens.

Socioeconomic disparities are another concern. Households of lower socioeconomic status are at increased risk for higher concentrations of indoor air pollutants (65). Homes with higher energy consumption and worse energy efficiency are disproportionately those of low-income, African American, and Hispanic individuals (128). Improvements in home energy efficiency and the transition from combustion-related indoor activities, such as cooking and heating, to clean electricity will need to consider environmental justice implications, specifically that poorer communities who are disproportionately affected may be financially limited in their options to improve ventilation, electrify their systems, or update their appliances. The U.S. Department of Energy Weatherization Assistance Program does provide low- to no-cost energy efficiency upgrades to low-income homeowners, and the Justice40 Initiative (Executive Order 14,008) sets a goal of 40% U.S. Federal Government investment in areas such as clean energy, energy efficiency, and sustainable housing, directed to disadvantaged communities (128, 129). In addition, the Inflation Reduction Act of 2022 renews and strengthens programs incentivizing home efficiency upgrades such as insulation, ventilation improvements, or upgrading appliances (130). For individual taxpayers, households could claim an expanded tax credit to help cover the cost of upgrades, including installing heat pumps and electric stoves. Households can also get a tax credit for installing rooftop solar panels and other sources of clean electricity. Additional tax incentives, government subsidies, and rebates exist; however, they vary considerably by state and local municipality.

There is a need for further research, especially randomized controlled trials to evaluate the most effective strategies to reduce indoor sources of air pollution, the findings of which may help prioritize investment and regulatory efforts. Although the scope of this workshop is focused on the United States, millions of people worldwide are exposed to toxic levels of indoor (or household) air pollution, which contributes to outdoor air pollution (131). Studies in low- and middle-income countries have lessons and methodologies that are applicable to high-income countries. In Guatemala, the transition from open-fire cooking to using a chimney stove reduced indoor air pollution by 50%, with reductions in severe pneumonia (a secondary endpoint), but did not reduce physician-diagnosed pneumonia (primary endpoint), potentially because chimney stoves vent the smoke outdoors, where it contributes to ambient air pollution and can infiltrate back into homes through leaky construction (132). Despite potential reductions in personal exposure and improvements in health (131), efforts in Ghana to transition away from solid fuels as the primary source of cooking energy to cleaner sources have also been revealing: Knowledge building around health benefits and dispelling fears of new technology are important to adopting cleaner fuel sources (133). These studies in low- and middle-income countries can also inform future indoor air pollution research in the United States.

Environmental Justice

Indoor concentrations of pollutants discussed in this report, including VOCs and NO_2, are higher in households of lower socioeconomic status, because of both indoor and outdoor sources; building quality; air infiltration pathways; and the presence, condition, and use of ventilation (65). Interventions that address indoor air quality (e.g., building codes that favor installation of electric stoves over gas stoves) will need to be implemented in a just and equitable manner, particularly in disadvantaged communities and historically redlined neighborhoods, where ambient air pollution concentrations are higher (134, 135). To achieve this, efforts to mitigate the increasing proportion of indoor contributions to outdoor air quality will need to involve equal access to the decision-making process to improve public health across all communities.

Conclusions

Public health is threatened by poor indoor air quality and its contributions to outdoor air pollution. Air pollutants generated indoors also contribute to climate change, itself a public health crisis. Although indoor air quality is not directly regulated under the Clean Air Act in the United States, states and

Table 3. Recommendations for actions to inform interventions targeting indoor air quality

Number	Recommendation
1	Research quantifying the potential health benefits of switching from cooking with natural gas to cleaner cooking methods (e.g., induction stoves)
2	Greater knowledge on the most effective policies to promote switching from biomass burning to cleaner home-heating systems
3	Supplementing existing routine network data (e.g., through the U.S. EPA Chemical Speciation Network) with additional chemical speciation (either classes of organic aerosol or specific compounds) to facilitate identification of source contributions and to enable source- and composition-specific $PM_{2.5}$ health effects evaluation
4	Citizen science and community engagement opportunities (e.g., use of low-cost monitoring sensors such as the Purple Air) to obtain real-time community particulate matter concentrations
5	Education surrounding residential pollutant-generating activities and potential strategies to refrain from high-emitting activities during vulnerable periods (e.g., voluntary burn ban during air inversion)
6	Research on consumer products that emit volatile organic compounds, including the health effects

Definition of abbreviations: EPA = Environmental Protection Agency; $PM_{2.5}$ = particulate matter with an aerodynamic diameter $\leqslant 2.5\ \mu m$.

local jurisdictions can regulate indoor air sources on the basis of their contributions to outdoor air pollution. There are feasible and cost-effective interventions to reduce air pollution generated indoors, ranging from appliance change-out programs to source control and air filtration, to the expansion of economic incentives for electrification (Table 3) (11, 130). These interventions are likely to require a combination of incentive-based mechanisms (e.g., the Inflation Reduction Act) and more direct regulation (e.g., limits on new installations of natural gas infrastructure in buildings). Studies, including clinical trials of single and multifaceted interventions, are also needed to quantify the impact on exposure reduction and the health benefits. Moving toward combustion-free buildings would provide a major step forward toward making both our indoor and outdoor air healthier and would also contribute toward mitigating climate change. The committee emphasizes that the overall benefits of a transition to combustion-free homes and businesses will be even greater if electricity to power such buildings can be obtained from renewable energy sources, although there are near-term economic and infrastructure-related barriers that may be substantial in the short term and must be overcome. Finally, VOCs represent an underappreciated type of indoor air pollution with potentially chronic harmful health effects. Reducing the presence of VOCs, whether through fragrance-free indoor spaces or by eliminating certain products and sources, reduces exposure to species with known and unknown health impacts. We should strive for pollution-free, fragrance-free indoor spaces.

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References

1 Leech JA, Nelson WC, Burnett RT, Aaron S, Raizenne ME. It's about time: a comparison of Canadian and American time-activity patterns. *J Expo Anal Environ Epidemiol* 2002;12:427–432.

2 National Academies of Sciences, Engineering, and Medicine. Why indoor chemistry matters. Washington, DC: National Academies Press; 2022.

3 Marin A, Rector L, Morin B, Allen G. Residential wood heating: an overview of U.S. impacts and regulations. *J Air Waste Manag Assoc* 2022;72:619–628.

4 Burkhard E. Introduction to special issue on residential wood combustion. *J Air Waste Manag Assoc* 2022;72:617–618.

5 2017 National Emissions Inventory Report. Washington, DC: U.S. Environmental Protection Agency; 2017. https://gispub.epa.gov/neireport/2017/.

6 2020 Residential energy consumption survey: Table HC1.1 Fuels used and end uses in U.S. homes, by housing unit type, 2020. Washington, DC: U.S. Energy Information Administration; 2020. Available from: https://www.eia.gov/consumption/residential/data/2020/#fueluses.

7 Biomass explained: wood and wood waste. Washington, DC: U.S. Energy Information Administration, 2022. Available from: https://www.eia.gov/energyexplained/biomass/wood-and-wood-waste.php/.

8 Rokoff LB, Koutrakis P, Garshick E, Karagas MR, Oken E, Gold DR, *et al.* Wood stove pollution in the developed world: a case to raise awareness among pediatricians. *Curr Probl Pediatr Adolesc Health Care* 2017;47:123–141.

9 Ferro AR, Zíková N, Masiol M, Satsangi GP, Twomey T, Chalupa DC, *et al.* Residential indoor and outdoor PM measured using low-cost monitors during the heating season in Monroe County, NY. *Aerosol Air Qual Res* 2022;22:220210.

10 Wang Y, Hopke PK, Rattigan OV, Chalupa DC, Utell MJ. Multiple-year black carbon measurements and source apportionment using delta-C in Rochester, New York. *J Air Waste Manag Assoc* 2012;62:880–887.

11 Ward TJ, Palmer CP, Houck JE, Navidi WC, Geinitz S, Noonan CW. Community woodstove changeout and impact on ambient concentrations of polycyclic aromatic hydrocarbons and phenolics. *Environ Sci Technol* 2009;43:5345–5350.

12 Longhin E, Gualtieri M, Capasso L, Bengalli R, Mollerup S, Holme JA, *et al.* Physico-chemical properties and biological effects of diesel and biomass particles. *Environ Pollut* 2016;215:366–375.

13 Maciejczyk P, Chen L-C, Thurston G. The role of fossil fuel combustion metals in $PM_{2.5}$ air pollution health associations. *Atmosphere (Basel)* 2021;12:1086.

14 Burn wise. Washington, DC: U.S. Environmental Protection Agency; 2022. Available from: https://www.epa.gov/burnwise.

15 Shen G, Xue M, Wei S, Chen Y, Zhao Q, Li B, *et al.* Influence of fuel moisture, charge size, feeding rate and air ventilation conditions on the emissions of PM, OC, EC, parent PAHs, and their derivatives from residential wood combustion. *J Environ Sci (China)* 2013;25:1808–1816.

16 Frey A, Tissari J, Saarnio K, Timonen HJ, Tolonen-Kivimäki O, Aurela MA, *et al.* Chemical composition and mass size distribution of fine particulate matter emitted by a small masonry heater. *Boreal Environ Res* 2009;14:255–271.

17 Johansson LS, Leckner B, Gustavsson L, Cooper D, Tullin C, Potter A. Emission characteristics of modern and old-type residential boilers fired with wood logs and wood pellets. *Atmos Environ* 2004;38: 4183–4195.

18 Sundararajan R, D'Couto H, Mugerwa J, Tayebwa M, Lam N, Wallach E, *et al.* Use, cost-effectiveness, and end user perspectives of a home solar lighting intervention in rural Uganda: a mixed methods, randomized controlled trial. *Environ Res Lett* 2022;17:015002.

19 Western Massachusetts changeout program. Washington, DC: U.S. Environmental Protection Agency; 2022. Available from: https://www.epa.gov/system/files/documents/2022–03/ma-berkshire-case-study.pdf.

20 Clearing the smoke: the wood stove changeout in Libby, Montana. Arlington, VA: Hearth, Patio & Barbecue Association; 2008. Available from: https://www.hpba.org/Portals/26/Documents/Government%20Affairs/Libby_Report-Final.pdf?ver=2017-06-13-082448-233.

21 U.S. households' heating equipment choices are diverse and vary by climate region. Washington, DC: U.S. Energy Information Administration; 2017. Available from: https://www.eia.gov/todayinenergy/detail.php?id=30672.

22 Lebel ED, Lu HS, Speizer SA, Finnegan CJ, Jackson RB. Quantifying methane emissions from natural gas water heaters. *Environ Sci Technol* 2020;54:5737–5745.

23 Global methane assessment: benefits and costs of mitigating methane emissions. Nairobi, Kenya: United Nations Environment Programme and Climate and Clean Air Coalition; 2021. Available from: https://www.unep.org/resources/report/global-methane-assessment-benefits-and-costs-mitigating-methane-emissions.

24 Weller ZD, Im S, Palacios V, Stuchiner E, von Fischer JC. Environmental injustices of leaks from urban natural gas distribution systems: patterns among and within 13 U.S. metro areas. *Environ Sci Technol* 2022;56: 8599–8609.

25 Lebel ED, Finnegan CJ, Ouyang Z, Jackson RB. Methane and NO_x emissions from natural gas stoves, cooktops, and ovens in residential homes. *Environ Sci Technol* 2022;56:2529–2539.

26 Lin W, Brunekreef B, Gehring U. Meta-analysis of the effects of indoor nitrogen dioxide and gas cooking on asthma and wheeze in children. *Int J Epidemiol* 2013;42:1724–1737.

27 Singer BC, Pass RZ, Delp WW, Lorenzetti DM, Maddalena RL. Pollutant concentrations and emission rates from natural gas cooking burners without and with range hood exhaust in nine California homes. *Build Environ* 2017;122:215–229.

28 Neas LM, Dockery DW, Ware JH, Spengler JD, Speizer FE, Ferris BG Jr. Association of indoor nitrogen dioxide with respiratory symptoms and pulmonary function in children. *Am J Epidemiol* 1991;134:204–219.

29 Mullen NA, Li J, Russell ML, Spears M, Less BD, Singer BC. Results of the California Healthy Homes Indoor Air Quality Study of 2011–2013: impact of natural gas appliances on air pollutant concentrations. *Indoor Air* 2016;26:231–245.

30 Criteria air pollutants. Washington, DC: U.S. Environmental Protection Agency; 2022. Available from: https://www.epa.gov/criteria-air-pollutants.

31 2022 State strategy for the state implementation plan (2022 state SIP strategy). Sacramento, CA: California Air Resources Board; 2022 [accessed 2023 June 29]. Available from: https://ww2.arb.ca.gov/resources/documents/2022-state-strategy-state-implementation-plan-2022-state-sip-strategy.

32 Park SS, Vijayan A, Mara SL, Herner JD. Investigating the real-world emission characteristics of light-duty gasoline vehicles and their relationship to local socioeconomic conditions in three communities in Los Angeles, California. *J Air Waste Manag Assoc* 2016;66:1031–1044.

33 Rosenow J, Gibb D, Nowak T, Lowes R. Heating up the global heat pump market. *Nat Energy* 2022;7:901–904.

34 Barr CD, Dominici F. Cap and trade legislation for greenhouse gas emissions: public health benefits from air pollution mitigation. *JAMA* 2010;303:69–70.

35 Landrigan PJ, Frumkin H, Lundberg BE. The false promise of natural gas. *N Engl J Med* 2020;382:104–107.

36 New York City Comptroller Brad Lander. Comments on New York City's Executive Budget for Fiscal Year 2024 and Financial Plan for Fiscal Years 2023 – 2027. New York: Office of the New York City Comptroller; 2023. Available from: https://comptroller.nyc.gov/reports/comments-on-new-york-citys-executive-budget-for-fiscal-year-2024-and-financial-plan-for-fiscal-years-2023–2027/.

37 Chowdhury S, Dey S, Guttikunda S, Pillarisetti A, Smith KR, Di Girolamo L. Indian annual ambient air quality standard is achievable by completely mitigating emissions from household sources. *Proc Natl Acad Sci USA* 2019;116:10711–10716.

38 Engelberg J, Brassell E. Differences in fuel usage in the United States housing stock: American Housing Survey report. Washington, DC: U.S. Department of Housing and Urban Development; 2019. Available from: https://www.census.gov/programs-surveys/ahs/research/publications/h150-19.html.

39 Torkmahalleh MA. Cooking aerosol. In: Zhang Y, Hopke PK, Mandin C, editors. Handbook of indoor air quality. Singapore: Springer Nature Singapore; 2022. pp. 387–425.

40 Nazaroff WW. Ten questions concerning indoor ultrafine particles. *Build Environ* 2023;243:110641.

41 Patel S, Sankhyan S, Boedicker EK, DeCarlo PF, Farmer DK, Goldstein AH, *et al.* Indoor particulate matter during HOMEChem: concentrations, size distributions, and exposures. *Environ Sci Technol* 2020;54:7107–7116.

42 Less B, Mullen N, Singer B, Walker I. Indoor air quality in 24 California residences designed as high-performance homes. *Sci Technol Built Environ* 2015;21:14–24.

43 Jiang J, Jung N, Boor BE. Using building energy and smart thermostat data to evaluate indoor ultrafine particle source and loss processes in a net-zero energy house. *ACS ES&T Eng* 2021;1:780–793.

44 Wan M-P, Wu C-L, Sze To G-N, Chan T-C, Chao CYH. Ultrafine particles, and PM2.5 generated from cooking in homes. *Atmos Environ* 2011;45:6141–6148.

45 Thakrar SK, Balasubramanian S, Adams PJ, Azevedo IML, Muller NZ, Pandis SN, *et al.* Reducing mortality from air pollution in the United States by targeting specific emission sources. *Environ Sci Technol Lett* 2020;7:639–645.

46 Robinson ES, Gu P, Ye Q, Li HZ, Shah RU, Apte JS, *et al.* Restaurant impacts on outdoor air quality: elevated organic aerosol mass from restaurant cooking with neighborhood-scale plume extents. *Environ Sci Technol* 2018;52:9285–9294.

47 Elser M, Bozzetti C, El-Haddad I, Maasikmets M, Teinemaa E, Richter R, *et al.* Urban increments of gaseous and aerosol pollutants and their sources using mobile aerosol mass spectrometry measurements. *Atmos Chem Phys* 2016;16:7117–7134.

48 Vert C, Meliefste K, Hoek G. Outdoor ultrafine particle concentrations in front of fast food restaurants. *J Expo Sci Environ Epidemiol* 2016;26: 35–41.

49 ElSharkawy MF, Ibrahim OA. Impact of the restaurant chimney emissions on the outdoor air quality. *Atmosphere (Basel)* 2022;13:261.

50 Guo R, Qi Y, Zhao B, Pei Z, Wen F, Wu S, *et al.* High-resolution urban air quality mapping for multiple pollutants based on dense monitoring data and machine learning. *Int J Environ Res Public Health* 2022;19:8005.

51 New York City administrative code. Title 24 environmental protection and utilities. Chapter 1: Air pollution control. New York: New York City Environmental Protection; 2016 [updated Nov 2016]. Available from: https://www1.nyc.gov/assets/dep/downloads/pdf/air/air-pollution-control-code.pdf.

52 California Air Resources Board, San Joaquin Valley Air Pollution Control District. Progress Report and Technical Submittal for the 2012 PM2.5 Standard San Joaquin Valley; 2021. [Accessed 2024 Nov 1]. https://ww2.arb.ca.gov/sites/default/files/2021-11/SJV_Progress_Report_Technical_Submittal_2012_PM25_Standard.pdf.
53 Singer BC, Chan WR, Kim YS, Offermann FJ, Walker IS. Indoor air quality in California homes with code-required mechanical ventilation. *Indoor Air* 2020;30:885–899.
54 Zhao H, Chan WR, Delp WW, Tang H, Walker IS, Singer BC. Factors impacting range hood use in California houses and low-income apartments. *Int J Environ Res Public Health* 2020;17:8870.
55 Paulin LM, Diette GB, Scott M, McCormack MC, Matsui EC, Curtin-Brosnan J, *et al.* Home interventions are effective at decreasing indoor nitrogen dioxide concentrations. *Indoor Air* 2014;24:416–424.
56 Park HJ, Lee HY, Suh CH, Kim HC, Kim HC, Park YJ, *et al.* The effect of particulate matter reduction by indoor air filter use on respiratory symptoms and lung function: a systematic review and meta-analysis. *Allergy Asthma Immunol Res* 2021;13:719–732.
57 McDonald E, Cook D, Newman T, Griffith L, Cox G, Guyatt G. Effect of air filtration systems on asthma: a systematic review of randomized trials. *Chest* 2002;122:1535–1542.
58 Residential air cleaners: a technical summary. Washington, DC: U.S. Environmental Protection Agency; 2018. Available from: https://www.epa.gov/sites/default/files/2018–07/documents/residential_air_cleaners_-_a_technical_summary_3rd_edition.pdf.
59 Balmes JR, Holm SM, McCormack MC, Hansel NN, Gerald LB, Krishnan JA. Cooking with natural gas: just the facts, please. *Am J Respir Crit Care Med* 2023;207:996–997.
60 2021-2022 Residential induction cooking tops. Washington, DC: U.S. Environmental Protection Agency and U.S. Department of Energy; 2022. Available from: https://www.energystar.gov/about/2021_residential_induction_cooking_tops.
61 Martínez-Gómez J, Ibarra D, Villacis S, Cuji P, Cruz PR. Analysis of LPG, electric and induction cookers during cooking typical Ecuadorian dishes into the national efficient cooking program. *Food Policy* 2016; 59:88–102.
62 Inflation Reduction Act of 2022, H.R. 5376, 117th Cong., P.L. 117-169 136 Stat. 1818 (2022). Available from: https://www.congress.gov/bill/117th-congress/house-bill/5376/text.
63 Liu Y, Misztal PK, Arata C, Weschler CJ, Nazaroff WW, Goldstein AH. Observing ozone chemistry in an occupied residence. *Proc Natl Acad Sci USA* 2021;118:e2018140118.
64 Hun DE, Siegel JA, Morandi MT, Stock TH, Corsi RL. Cancer risk disparities between Hispanic and non-Hispanic white populations: the role of exposure to indoor air pollution. *Environ Health Perspect* 2009; 117:1925–1931.
65 Adamkiewicz G, Zota AR, Fabian MP, Chahine T, Julien R, Spengler JD, *et al.* Moving environmental justice indoors: understanding structural influences on residential exposure patterns in low-income communities. *Am J Public Health* 2011; 101(Suppl 1)S238–S245.
66 Nazaroff WW, Weschler CJ. Indoor ozone: concentrations and influencing factors. *Indoor Air* 2022;32:e12942.
67 Peng Z, Day DA, Symonds G, Jenks OJ, Stark H, Handschy AV, *et al.* Significant production of ozone from germicidal UV lights at 222 nm. *Environ Sci Technol Lett* 2023;10:668–674.
68 Carslaw N. Indoor gas-phase chemistry. In: Zhang Y, Hopke PK, Mandin C, editors. Handbook of indoor air quality. Singapore: Springer Nature Singapore; 2022. pp. 837–854.
69 Morrison GC. Indoor surface chemistry. In: Zhang Y, Hopke PK, Mandin C, editors. Handbook of indoor air quality. Singapore: Springer Nature Singapore; 2022. pp. 885–902.
70 Weschler CJ, Nazaroff WW. Human skin oil: a major ozone reactant indoors. *Environ Sci Atmos* 2023;3:640–661.
71 Zannoni N, Li M, Wang N, Ernle L, Bekö G, Wargocki P, *et al.* Effect of ozone, clothing, temperature, and humidity on the total OH reactivity emitted from humans. *Environ Sci Technol* 2021;55:13614–13624.
72 Wang N, Zannoni N, Ernle L, Bekö G, Wargocki P, Li M, *et al.* Total OH reactivity of emissions from humans: in situ measurement and budget analysis. *Environ Sci Technol* 2021;55:149–159.
73 Zannoni N, Lakey PSJ, Won Y, Shiraiwa M, Rim D, Weschler CJ, *et al.* The human oxidation field. Science 2022;377:1071–1077.
74 Cohen Hubal EA, Richard A, Aylward L, Edwards S, Gallagher J, Goldsmith MR, *et al.* Advancing exposure characterization for chemical evaluation and risk assessment. *J Toxicol Environ Health B Crit Rev* 2010;13:299–313.
75 Richard AM, Judson RS, Houck KA, Grulke CM, Volarath P, Thillainadarajah I, *et al.* ToxCast chemical landscape: paving the road to 21st century toxicology. *Chem Res Toxicol* 2016;29:1225–1251.
76 Smith MN, Cohen Hubal EA, Faustman EM. A case study on the utility of predictive toxicology tools in alternatives assessments for hazardous chemicals in children's consumer products. *J Expo Sci Environ Epidemiol* 2020;30:160–170.
77 Wang Z, Walker GW, Muir DCG, Nagatani-Yoshida K. Toward a global understanding of chemical pollution: a first comprehensive analysis of national and regional chemical inventories. *Environ Sci Technol* 2020; 54:2575–2584.
78 Fiedler N, Laumbach R, Kelly-McNeil K, Lioy P, Fan ZH, Zhang J, *et al.* Health effects of a mixture of indoor air volatile organics, their ozone oxidation products, and stress. *Environ Health Perspect* 2005;113: 1542–1548.
79 Laumbach RJ, Fiedler N, Gardner CR, Laskin DL, Fan ZH, Zhang J, *et al.* Nasal effects of a mixture of volatile organic compounds and their ozone oxidation products. *J Occup Environ Med* 2005;47: 1182–1189.
80 Pennington EA, Seltzer KM, Murphy BN, Qin M, Seinfeld JH, Pye HOT. Modeling secondary organic aerosol formation from volatile chemical products. *Atmos Chem Phys* 2021;21:18247–18261.
81 Seltzer KM, Murphy BN, Pennington EA, Allen C, Talgo K, Pye HOT. Volatile chemical product enhancements to criteria pollutants in the United States. *Environ Sci Technol* 2022;56:6905–6913.
82 Steinemann A. Fragranced consumer products: exposures and effects from emissions. *Air Qual Atmos Health* 2016;9:861–866.
83 van Amerongen CCA, Ofenloch RF, Cazzaniga S, Elsner P, Gonçalo M, Naldi L, *et al.* Skin exposure to scented products used in daily life and fragrance contact allergy in the European general population - The EDEN Fragrance Study. *Contact Dermat* 2021;84:385–394.
84 Caress SM, Steinemann AC. Prevalence of fragrance sensitivity in the American population. *J Environ Health* 2009;71:46–50.
85 Weisel CP, Zhang J, Turpin BJ, Morandi MT, Colome S, Stock TH, *et al.* Relationships of indoor, outdoor, and personal air (RIOPA). Part I. Collection methods and descriptive analyses. *Res Rep Health Eff Inst* 2005; (130, Pt 1):1–107, discussion 109–127.
86 Hurley JF, Smiley E, Isaacman-VanWertz G. Modeled emission of hydroxyl and ozone reactivity from evaporation of fragrance mixtures. *Environ Sci Technol* 2021;55:15672–15679.
87 Qiu W, Zhao Y, Yang M, Farajzadeh M, Pan C, Wayne NL. Actions of bisphenol A and bisphenol S on the reproductive neuroendocrine system during early development in zebrafish. *Endocrinology* 2016;157:636–647.
88 Khare P, Gentner DR. Considering the future of anthropogenic gas-phase organic compound emissions and the increasing influence of non-combustion sources on urban air quality. *Atmos Chem Phys* 2018;18:5391–5413.
89 McDonald BC, de Gouw JA, Gilman JB, Jathar SH, Akherati A, Cappa CD, *et al.* Volatile chemical products emerging as largest petrochemical source of urban organic emissions. *Science* 2018; 359(6377):760–764.
90 Coggon MM, Gkatzelis GI, McDonald BC, Gilman JB, Schwantes RH, Abuhassan N, *et al.* Volatile chemical product emissions enhance ozone and modulate urban chemistry. *Proc Natl Acad Sci USA* 2021; 118:e2026653118.
91 Pye HOT, Appel KW, Seltzer KM, Ward-Caviness CK, Murphy BN. Human-health impacts of controlling secondary air pollution precursors. *Environ Sci Technol Lett* 2022;9:96–101.
92 Gkatzelis GI, Coggon MM, McDonald BC, Peischl J, Aikin KC, Gilman JB, *et al.* Identifying volatile chemical product tracer compounds in U.S. cities. *Environ Sci Technol* 2021;55:188–199.
93 Simoneit BRT, Schauer JJ, Nolte CG, Oros DR, Elias VR, Fraser MP, *et al.* Levoglucosan, a tracer for cellulose in biomass burning and atmospheric particles. *Atmos Environ* 1999;33:173–182.
94 Wang Y, Hopke PK, Rattigan OV, Xia X, Chalupa DC, Utell MJ. Characterization of residential wood combustion particles using the two-wavelength aethalometer. *Environ Sci Technol* 2011;45:7387–7393.
95 Kleindienst TE, Jaoui M, Lewandowski M, Offenberg JH, Lewis CW, Bhave P, *et al.* Estimates of the contributions of biogenic and anthropogenic hydrocarbons to secondary organic aerosol at a southeastern US location. *Atmos Environ* 2007;41:8288–8300.

96 Dai Q, Bi X, Song W, Li T, Liu B, Ding J, *et al.* Residential coal combustion as a source of primary sulfate in Xi'an, China. *Atmos Environ* 2019;196:66–76.

97 Li X, Han J, Hopke PK, Hu J, Shu Q, Chang Q, *et al.* Quantifying primary and secondary humic-like substances in urban aerosol based on emission source characterization and a source-oriented air quality model. *Atmos Chem Phys* 2019;19:2327–2341.

98 Integrated science assessment (ISA) for particulate matter (final report, Dec 2019). Washington, DC: U.S. Environmental Protection Agency; 2019.

99 Wilk A, Waligórski P, Lassak A, Vashistha H, Lirette D, Tate D, *et al.* Polycyclic aromatic hydrocarbons-induced ROS accumulation enhances mutagenic potential of T-antigen from human polyomavirus JC. *J Cell Physiol* 2013;228:2127–2138.

100 Rich DQ, Zhang W, Lin S, Squizzato S, Thurston SW, van Wijngaarden E, *et al.* Triggering of cardiovascular hospital admissions by source specific fine particle concentrations in urban centers of New York State. *Environ Int* 2019;126:387–394.

101 Croft DP, Zhang W, Lin S, Thurston SW, Hopke PK, van Wijngaarden E, *et al.* Associations between source-specific particulate matter and respiratory infections in New York State adults. *Environ Sci Technol* 2020;54:975–984.

102 Hopke PK, Croft DP, Zhang W, Lin S, Masiol M, Squizzato S, *et al.* Changes in the hospitalization and ED visit rates for respiratory diseases associated with source-specific $PM_{2.5}$ in New York State from 2005 to 2016. *Environ Res* 2020;181:108912.

103 Duncan SM, Tomaz S, Morrison G, Webb M, Atkin J, Surratt JD, *et al.* Dynamics of residential water-soluble organic gases: insights into sources and sinks. *Environ Sci Technol* 2019;53:1812–1821.

104 Nazaroff WW. Exploring the consequences of climate change for indoor air quality. *Environ Res Lett* 2013;8:015022.

105 Fisk WJ. Review of some effects of climate change on indoor environmental quality and health and associated no-regrets mitigation measures. *Build Environ* 2015;86:70–80.

106 Mansouri A, Wei W, Alessandrini J-M, Mandin C, Blondeau P. Impact of climate change on indoor air quality: a review. *Int J Environ Res Public Health* 2022;19:15616.

107 Laumbach R, Meng Q, Kipen H. What can individuals do to reduce personal health risks from air pollution? *J Thorac Dis* 2015;7:96–107.

108 Henderson DE, Milford JB, Miller SL. Prescribed burns and wildfires in Colorado: impacts of mitigation measures on indoor air particulate matter. *J Air Waste Manag Assoc* 2005;55:1516–1526.

109 Schwartz-Narbonne H, Abbatt JPD, DeCarlo PF, Farmer DK, Mattila JM, Wang C, *et al.* Modeling the removal of water-soluble trace gases from indoor air via air conditioner condensate. *Environ Sci Technol* 2021;55:10987–10993.

110 Romitti Y, Sue Wing I, Spangler KR, Wellenius GA. Inequality in the availability of residential air conditioning across 115 US metropolitan areas. *PNAS Nexus* 2022;1:pgac210.

111 Making our homes more efficient: clean energy tax credits for consumers. Washington, DC: U.S. Department of Energy; 2022. Available from: https://www.energy.gov/policy/articles/making-our-homes-more-efficient-clean-energy-tax-credits-consumers.

112 Cromar KR, Gladson LA, Hicks EA, Marsh B, Ewart G. Excess morbidity and mortality associated with air pollution above American Thoracic Society recommended standards, 2017–2019. *Ann Am Thorac Soc* 2022;19:603–613.

113 What are hazardous air pollutants? Washington, DC: U.S. Environmental Protection Agency; 2022 [accessed2023 June 2]. https://www.epa.gov/haps/what-are-hazardous-air-pollutants.

114 Clean air amendments of 1970, H.R.17255, 91st Cong., P.L. 91-604, §1, 84 Stat. 1676 (1970).

115 Logue JM, McKone TE, Sherman MH, Singer BC. Hazard assessment of chemical air contaminants measured in residences. *Indoor Air* 2011;21:92–109.

116 Salthammer T, Mentese S, Marutzky R. Formaldehyde in the indoor environment. *Chem Rev* 2010;110:2536–2572.

117 Gkatzelis GI, Coggon MM, McDonald BC, Peischl J, Gilman JB, Aikin KC, *et al.* Observations confirm that volatile chemical products are a major source of petrochemical emissions in U.S. cities. *Environ Sci Technol* 2021;55:4332–4343.

118 Standards of performance for new residential wood heaters, new residential hydronic heaters and forced-air furnaces [80 FR 13671]. *Fed Regist* 2015;80:13672–13753. Available from: https://www.federalregister.gov/documents/2015/03/16/2015–03733/standards-of-performance-for-new-residential-wood-heaters-new-residential-hydronic-heaters-and.

119 Zhang L, He MZ, Gibson EA, Perera F, Lovasi GS, Clougherty JE, *et al.* Evaluating the impact of the Clean Heat Program on air pollution levels in New York City. *Environ Health Perspect* 2021;129:127701.

120 Fisk WJ, Chan WR. Effectiveness and cost of reducing particle-related mortality with particle filtration. *Indoor Air* 2017;27:909–920.

121 Baudet A, Baurès E, Blanchard O, Le Cann P, Gangneux J-P, Florentin A. Indoor carbon dioxide, fine particulate matter and total volatile organic compounds in private healthcare and elderly care facilities. *Toxics* 2022;10:136.

122 Fermo P, Artíñano B, De Gennaro G, Pantaleo AM, Parente A, Battaglia F, *et al.* Improving indoor air quality through an air purifier able to reduce aerosol particulate matter (PM) and volatile organic compounds (VOCs): experimental results. *Environ Res* 2021;197:111131.

123 Jin L, Griffith SM, Sun Z, Yu JZ, Chan W. On the flip side of mask wearing: increased exposure to volatile organic compounds and a risk-reducing solution. *Environ Sci Technol* 2021;55:14095–14104.

124 Ye Q, Krechmer JE, Shutter JD, *et al.* Real-time laboratory measurements of VOC emissions, removal rates, and byproduct formation from consumer-grade oxidation-based air cleaners. *Environ Sci Technol Lett* 2021;8:1020–1025.

125 Gillingham KT, Huang P, Buehler C, Peccia J, Gentner DR. The climate and health benefits from intensive building energy efficiency improvements. *Sci Adv* 2021;7:eabg0947.

126 Gold DR. Indoor air pollution. *Clin Chest Med* 1992;13:215–229.

127 Soule EK, Maloney SF, Spindle TR, Rudy AK, Hiler MM, Cobb CO. Electronic cigarette use and indoor air quality in a natural setting. *Tob Control* 2017;26:109–112.

128 Bednar DJ, Reames TG, Keoleian GA. The intersection of energy and justice: modeling the spatial, racial/ethnic and socioeconomic patterns of urban residential heating consumption and efficiency in Detroit, Michigan. *Energy Build* 2017;143:25–34.

129 Interim implementation guidance for the Justice40 Initiative. Washington, DC: U.S. Executive Office of the President, Office of Management and Budget; 2021. Available from: https://www.whitehouse.gov/wp-content/uploads/2021/07/M-21–28.pdf.

130 Credits and deductions under the Inflation Reduction Act of 2022. Washington, DC: Internal Revenue Service; 2023 [accessed2023 June 21]. Available from: https://www.irs.gov/credits-and-deductions-under-the-inflation-reduction-act-of-2022.

131 Boamah-Kaali E, Jack DW, Ae-Ngibise KA, Quinn A, Kaali S, Dubowski K, *et al.* Prenatal and postnatal household air pollution exposure and infant growth trajectories: evidence from a rural Ghanaian pregnancy cohort. *Environ Health Perspect* 2021;129:117009.

132 Smith KR, McCracken JP, Weber MW, Hubbard A, Jenny A, Thompson LM, *et al.* Effect of reduction in household air pollution on childhood pneumonia in Guatemala (RESPIRE): a randomised controlled trial. *Lancet* 2011;378:1717–1726.

133 Tawiah T, Iddrisu S, Gyaase S, Twumasi M, Asante KP, Jack D. The feasibility and acceptability of clean fuel use among rural households. A pilot study in Central Ghana. *J Public Health Africa* 2022;13:2205.

134 Lane HM, Morello-Frosch R, Marshall JD, Apte JS. Historical redlining is associated with present-day air pollution disparities in U.S. cities. *Environ Sci Technol Lett* 2022;9:345–350.

135 Nardone A, Casey JA, Morello-Frosch R, Mujahid M, Balmes JR, Thakur N. Associations between historical residential redlining and current age-adjusted rates of emergency department visits due to asthma across eight cities in California: an ecological study. *Lancet Planet Health* 2020;4:e24–e31.

136 Ward TJ, Rinehart LR, Lange T. The 2003/2004 Libby, Montana $PM_{2.5}$ source apportionment research study. *Aerosol Sci Technol* 2006;40:166–177.

137 Ward T, Palmer C, Bergauff M, Hooper K, Noonan C. Results of a residential indoor $PM_{2.5}$ sampling program before and after a woodstove changeout. *Indoor Air* 2008;18:408–415.

138 Noonan CW, Navidi W, Sheppard L, Palmer CP, Bergauff M, Hooper K, *et al.* Residential indoor $PM_{2.5}$ in wood stove homes: follow-up of the Libby changeout program. *Indoor Air* 2012;22:492–500.