FUMES IN FOCUS

VISUALIZING AIR POLLUTION FROM GAS STOVES

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Special Thank You
Krystal Abrams, Arjorie Arberry-Baribeault, Emily Matlock, Paige Hopkins, Meet Panchal, Zach Mullholland, and all of our study participants

This report was funded in part by grants from the U.S. Energy Foundation, Meyer Memorial Trust and donor advised funds of the Oregon Community Foundation.

TABLE OF CONTENTS

EXECUTIVE SUMMARY

The American public is challenged to comprehend the negative impacts of gas stove indoor air pollution. There are two primary reasons for this lack of understanding. First is the fact that gas stove pollutants are not visible to the naked eye, and second is a decades-long campaign of disinformation and misleading advertising by gas utility companies operating under the umbrella economic interest group, the American Gas Association.

To better educate the public, Beyond Toxics compiled a literature review of gas stove pollutants and their health effects. We also employed a specialized camera capable of visualizing gas stove pollutants, and utilized two consumer grade air quality monitors.

We found that gas stoves produce acutely hazardous and chronically harmful levels of nitrogen dioxide inside the home. Emissions from gas stoves also raise levels of volatile organic compounds and carbon monoxide above background levels.

Air monitoring verified that these pollutants move away from the kitchen area to the dining room and other areas of the house and appear to concentrate in rooms where the air flow was trapped, such as bedrooms. We also found that kitchen range ventilation hoods do not adequately remove pollution from gas stoves. In addition to the report, we produced a 7 minute video documentary, *Fumes in Focus*, featuring our findings and participant reactions.

KEY FINDINGS

- 82% (14/17) of homes had chronically hazardous levels of nitrogen dioxide presenting a risk for vulnerable populations (children, elderly, people with existing respiratory conditions).

- 88% (15/17) of homes experienced increases in nitrogen dioxide associated with asthma symptoms for children. 12/17 saw increases in nitrogen dioxide associated with asthma symptoms for people of all ages.

- Nitrogen dioxide and volatile organic compounds, a class of chemicals that are often harmful to people, produced by gas stoves spread throughout homes including dining rooms, ground floor rooms, and upper floors.

- 94% (16/17) of the ventilation hoods in this study failed to capture all pollution from gas stove burners and ovens.

- 64% (11/17) of homes had the most common ventilation exhaust system, which is a flat mesh filter often built into a microwave installed over the stove. They failed to capture any pollutants from front burners and failed to completely capture pollution from back burners.

- No exhaust vents (0/17) captured emissions escaping from opening oven doors.

KEY RECOMMENDATIONS

- Amend local and state building codes to encourage installation of all-electric equipment for new residential construction.
- Protect your health by replacing gas-powered equipment in your home, or by using alternative electric appliances (airfryer, induction cooktops, electric kettle, crock pot, etc.) to help reduce daily exposures to gas stove pollutants.
- Mitigate exposure to indoor air pollution from gas stoves by increasing ventilation while cooking.
- Determine your eligibility for federal, state, and local tax incentives and rebates for home electrification with energy and appliance upgrades.

INTRODUCTION

Environmental and public health concerns related to indoor air quality are increasing as scientists and consumers grapple with the new data about sources of dangerous air pollutants accumulating in living spaces. Consumers have been lulled into thinking that these exposures are negligible due to a lack of federal health standards for indoor exposure to pollutants such as NO2, benzene, toluene, carbon monoxide, and other air toxics (Seals and Krasner, 2020).

This is far from the case. Gas equipment (stoves, ovens, water heaters, etc) can release unhealthy levels of air toxics in homes during normal usage. This is coupled with a slow dissipation and removal rate due to the sealed nature of indoor environments.

Furthermore, people typically spend 80% of their time indoors, particularly at night and during colder weather. This trend is likely to increase with extreme weather patterns and changing work norms that allow workers to do their jobs from their homes. As a result, indoor air quality now has a greater impact on people's health (Liu et al., 2012).

This report builds on a previous Beyond Toxics study, ***Seeing is Believing: Visualizing Indoor Air Pollution from Gas Stoves*** (Leavitt, et al., 2023), which used air quality equipment to monitor indoor pollution from the first few minutes after turning on a gas stove (Leavitt et al., 2023).

The study design involved preheating an oven to 350 degrees and turning on a single stove top burner for 3-5 minutes. This pilot project was a limited “proof of concept” study to determine study design and analytical equipment.

Based on the results, Beyond Toxics moved forward with a larger study to capture the typical scenario of cooking a meal using the stove top and oven.

In both studies, we found acutely hazardous and chronically risky concentrations of nitrogen dioxide (NO2), and increased levels of volatile organic compounds (VOCs) above background, from just a few minutes of using a gas stove. Indoor pollution increased with the use of the oven.

In addition to recreating the daily experience of cooking a meal, we sought to test other areas of the house for gas stove pollution. We added a second monitor which was deployed in dining rooms, and in some cases, participants chose to place a third monitor in a location of their choice.

In each of the 17 households who participated in this study, we cooked spaghetti, a sauce, and oven roasted vegetables with the gas stove.

We utilized a Flow 2 air quality monitor to measure the concentrations of nitrogen dioxide (NO2) and volatile organic compounds (VOCs), a Carbon Monoxide Experts 2015 Model to measure carbon monoxide, as well as the **Forward-Looking Infrared (FLIR) GF320**.

The FLIR GF320 camera is capable of visualizing many of the air pollutants escaping from gas stove tops and ovens during the cooking process including VOCs and NO2.

We also used the **FLIR GF320** to visualize the effectiveness of over-the-stove ventilation hoods for capturing air pollutants rising from burners and ovens that result from the combustion of methane gas (referred to as "natural gas" by the fossil fuel industry).

This report will summarize the relevant pollutants released into indoor and outdoor air from gas usage in homes, along with their public health and climate impacts. Following the sections on methodology, results, and discussion, the report concludes with a range of solutions to mitigate the effects of gas stoves, including technological and policy solutions.

Finally, as a general note, the terminology "gas stoves" is used to encompass both stoves with a gas range and gas oven, as well as stoves with a gas range and electric oven.

EFFECTS OF GAS STOVE POLLUTANTS ON PUBLIC HEALTH

Studies conducted as far back as the 1970s have shown that homes with gas stoves have higher rates of asthma and respiratory illnesses compared to homes with electric stoves. Numerous scientists concluded that increased rates of respiratory diseases are correlated with the exposure to air pollutants that are generated from burning gas to cook on a gas range. The same was true for other equipment such as water heaters or Heating Ventilation and Air Conditioning (HVAC) systems (Melia et al., 1977; Brady, 2023).

Gas executives immediately took interest in the emerging information. Dr. Carl Shy was one of these scientists documenting higher rates of respiratory illness in homes with gas stoves. Upon meeting with gas stove executives, he learned these proponents of expanding the consumer demand for gas had evidence that gas stoves produced dangerous levels of NO2, and that ventilation hoods could not remove the dangerous pollutants from kitchens.

Despite knowing full well about the health risk from breathing harmful chemicals from gas appliances on a regular basis, gas stove executives hired many of the same public relations firms as big tobacco. They devised and launched an aggressive marketing campaign, “Operation Attack,” that hired celebrities, such as Julia Child, to promote gas stoves as the epitome of luxury cooking. They also employed scientists to conduct alternative research disputing evidence showing the dangers of pollution (Brady, 2023).

In the late 1990s, studies confirmed that NO2 emissions from stoves can contribute to a significant increase in respiratory issues in children and adults (Hasselblad et al., 1992). Today, researchers are aware of a range of pollutants contributing to poor indoor air quality from gas equipment and the illnesses associated with chronic exposure to these pollutants.

As of 2023, there are more than 40 million gas stoves in American households, all of which contribute to nitrogen dioxide release, methane release, and public health concerns (Lebel et al., 2022). This is both an indoor and outdoor air quality issue because, once created, these pollutants first circulate indoors and then are either exhausted outside or escape through other outlets.

People who rely on gas equipment to prepare food in their homes are repeatedly exposed to toxic chemicals, including NO2, particulate matter (PM), carbon monoxide (CO), and VOCs.

These chemicals are formed from the heating and incomplete combustion of gas. Each of these pollutants has human health impacts associated with their exposure. Generally, pollutants are most harmful to vulnerable populations, such as children, elderly adults, and those with pre-existing adverse health conditions.

NITROGEN DIOXIDE

Nitrogen dioxide (NO2) is one type of reactive gas in a family of nitrogen chemicals collectively referred to as oxides of nitrogen or NOx. They share the molecular composition of having both nitrogen and oxygen atoms.

Gas stoves produce many types of NOx. The most concerning for public health implications is NO2, which enters indoor air mainly through gas stoves, followed by wood stoves, fireplaces using all fuels, and lastly ambient NO2 from outside background industrial and transportation sources (Alberts, 1994).

In all 17 households analyzed in this study, the only sources of NO2 in households during the period of data collection were gas equipment and ambient background pollution.

The U.S. EPA and many scientists are warning people of the effects of NO2 exposure on human health, and have been for decades. Nitrogen dioxide frequently released inside a home triggers respiratory diseases and illness (Lebel et al., 2022).

Studies have demonstrated a clear correlation between increased NO2 exposure, even as small as 10 parts per billion (ppb), and increased rates of mortality in older adults (Huangfu & Atkinson, 2020; Atkinson et al., 2018).

Recent studies have shown that children's asthma worsens with incremental increases of NO2 in the air. Increases of just 5 ppb over background levels of at least 6 ppb are observed to have an effect on children's asthma (Belanger et al., 2014).

Other researchers have found in some instances, regardless of background levels, there is a measurable increase in asthma with an NO2 increases of 15 parts per billion (ppb) (Lin et al., 2013; Li et al., 2006).

In a study published by The Rocky Mountain Institute (RMI), scientists measured peaks in NO2 levels when cooking various foods indoors (Seals and Krasner, 2020). NO2 peaks, measured in ppb, vary with different food preparations (Table 1). Each cooking scenario resulted in NO2 concentrations above safe exposure levels.

U.S. EPA National Ambient Air Quality Standards list 50 ppb as the average annual limit for NO2 in outdoor air (U.S. EPA, 2023). The EPA advises adult individuals to avoid exposure to NO2 levels at or above 100 ppb lasting an hour or longer (U.S. EPA Office of Air and Radiation, 2010).

It is important to acknowledge that this recommendation is for outdoor exposure only. The EPA has not established indoor air quality standards for NO2. The lack of indoor air quality standards creates a regulatory gap that has contributed to the lack of public awareness of the emissions from gas equipment, what indoor levels are verified as safe, and the level of human exposure within their homes. However, the U.S. EPA urges caution and states, “Average level in homes without combustion appliances is about half that of outdoors. In homes with gas stoves, kerosene heaters or unvented gas space heaters, indoor levels often exceed outdoor levels.” (U.S. EPA, 2023).

Table. 1.
O2 peak levels [in parts per billion (ppb)] from cooking various foods. Data from the Rocky Mountain Institute (RMI) (Seals and Krasner, 2020).

Measured NO2 Emissions from Gas Stoves	Peak (ppb)	U.S. EPA National Ambient 1-Hour Air Quality Standards for NO2 Exposure in Outdoor Air
Baking cake in oven	230	100
Baking meat in oven	296	100
Frying bacon	104	100
Boiling water	184	100

METHANE AND OTHER HYDROCARBONS

The chemical composition of gas is a combination of hydrocarbons containing 85 to 90 percent methane, with the remainder being other hydrocarbons, VOCs, nitrogen, and trace inert gasses (U.S EPA, 2020). According to the National Cancer Institute, exposure to these hydrocarbons may increase the risk of certain types of cancer (NCI, 2023).

Gas stoves leak 0.8% to 1.3% of the total gas used as unburned fuel. The percent of leakage is equivalent to the tailpipe emissions of about 500,000 cars yearly in the U.S. (Lebel et al., 2022) Methane molecules are 80x more powerful than carbon dioxide, CO2 (Environmental Defense Fund, 2023).

Methane emissions significantly contribute to climate change which presents multi-faceted risks to public health. The World Health Organization (WHO) states that climate change drives disasters such as extreme heat, increased hurricanes, extreme droughts, flash flooding, and rising sea levels. These all affect major social and environmental determinants of health – including clean air, safe drinking water, sufficient food and vector-borne illnesses (WHO, 2021).

$PM_{2.5}$ AND PM_{10}

The health effects of the small airborne particulate matter referred to as PM2.5 (measuring 2.5 microns in diameter) and PM10 (measuring 10 microns in diameter) are well studied. It has been found that there is a strong association between PM2.5 and increased rates of respiratory disorders, cardiovascular disorders, and cerebrovascular disorders, as well as mortality rates (Dirgawati et al., 2019; Sharma et al., 2020).

Epidemiological studies demonstrate an elevated risk for cardiovascular events with more exposure to PM2.5. These elevated cardiovascular events include stroke, arrhythmia, myocardial infarction (MI), and heart failure. Several studies have demonstrated that living in locations with high, long-term average PMx levels elevates the risk for cardiovascular morbidity and mortality (Simkhovich et al. 2008; Sharma et al., 2020).

PM10 pollution, as a bigger size of particulate matter of 10 microns in diameter or larger, is observed to have immediate respiratory effects such as coughing. Children are especially vulnerable to the acute respiratory health effects associated with respirable particulate pollution (Pope III & Dockery, 1992).

The long-term adverse health effects include: an increase in asthma medication usage; an increase in the number of asthma attacks; flare ups of chronic obstructive pulmonary disease; hospitalization for cardiovascular issues; and death from heart attacks, strokes, or respiratory issues due to these larger particles entering the lungs and heart (Donaldson et al,. 2001).

Notably, the combustion of fossil fuels is a substantial source of PM of all sizes, and Zheng et al. (2010), found that gas stoves produced twice as much PM2.5 as their electrical counterparts when cooking the same meal. In the same study, they noted gas stoves also produced more PM10 and ultrafine particulates, also known as PM1 (Zheng et al., 2010; Hu et al., 2012).

Fine and ultrafine particles are small enough to travel into the lung tissue and lodge in the alveoli, tiny, balloon-shaped air sacs located at the end of the bronchioles, that exchange oxygen and carbon dioxide with the blood stream.

VOLATILE ORGANIC COMPOUNDS

Volatile organic compounds (VOCs) are a class of organic compounds_that are produced from burning fossil fuels. VOCs are also found to off-gas from many manufacturing processes and consumer products.

VOC chemicals have a low boiling point and a high vapor pressure at room temperature which results in the shared trait of easily becoming vapors or gasses (volatility) capable of traveling away from their emission source (Wi et al., 2020).

Concentrations of VOCs are generally higher indoors than they are outdoors, which is why they are an important pollutant to mention when discussing indoor air pollution (Liu et al., 2012).

Breathing VOCs can irritate the eyes, nose, and throat; can cause difficulty breathing and nausea; and can damage the central nervous system along with other organs.

In addition, some VOCs can react with other gasses and form different chemicals, acting as dangerous air pollutants once they are in the air. They are associated with the onset and exacerbation of asthma when exposure occurs, especially among children (Chin et al., 2013).

Pregnant women exposed to VOCs can have those chemicals travel via the body into the fetus, which can lead their unborn babies to experience health impacts, such as anemia or low birth weight (Boyle et al., 2016).

The most frequently detected VOCs are hexane, benzene, and toluene, which were found in 98%, 95%, and 94% of sampled houses. Other VOCs, such as xylene and ethylbenzene, commonly associated with fossil fuel products, were additionally found in 75% and 54% of households with gas stoves.

Researchers found 21 different federally hazardous VOCs leaked from gas stoves while the stove was in off mode (Lebel et al., 2022). The authors concluded that, "Unburned natural gas emissions from household appliances, even while they are off, have the potential to be a health-relevant source of benzene in indoor air." Cooking with a gas stove increases indoor levels of VOCs, particularly in an unvented or poorly vented area (Lebel et al., 2022, Guo et al., 2009).

Benzene is known to cause blood disorders and blood cancers. Researchers in California estimate that the inventory of the state's gas stoves emit the equivalent benzene emissions of 60,000 fossil fuel cars (Lebel et al., 2022). Exposure to benzene has a cumulative effect, meaning that small or chronic exposures can result in serious health disorders. Kashtan et al. (2023) found that a single stove burner on high emitted more benzene than what scientists have found in secondhand smoke from cigarettes.

Formaldehyde is another harmful VOC emitted from the use of gas stoves. Formaldehyde naturally occurs through the oxidation of hydrocarbons, which make up 99% of natural gas (U.S. EPA, 2020). Formaldehyde is used globally to produce resins for adhesives and also works as a preservative and disinfectant in cosmetic products, pesticides, biological specimens and human or veterinary drugs (Liu et al., 2012). All of these products can be found in millions of homes. There is a large spectrum of indoor formaldehyde emission sources due to its usage in many common-use products.

All of this makes formaldehyde one of the most influential indoor air pollutants (Liu et al., 2012). Formaldehyde leads to cancer in people of all ages and causes respiratory infections of the lower lungs in infants (National Cancer Institute, 2011; Roda et al., 2011). Low heat settings on gas burners, particularly for simmering sauces and soups, can substantially expose individuals to formaldehyde (Poppendieck and Gong, 2018; Seals and Krasner, 2020).

CARBON MONOXIDE

Gas stoves emit low levels of carbon monoxide (CO) when turned on, and can emit high levels if the stove is malfunctioning. Oregon requires homes rented or sold to have CO alarms, however, alarms are typically calibrated to sound only when CO levels are enough to cause serious acute health problems, and not for lower chronic exposure thresholds (Seals and Krasner, 2020).

A study in California, where 70% of residents have gas stoves, found 5% of 316 homes exceeded the state's levels of 1-hour (20 ppm) and 8-hour (9 ppm) CO exposure limits (Beal, 2022; Mullen et al., 2013; Seals and Krasner, 2020). Typical household CO alarms are not calibrated to detect these chronic, low-level exposures.

Table 1.
The table below summarizes the most common air pollutants associated with cooking on gas stoves detailed in the paragraphs above. The health impacts column includes both acute and chronic symptoms from exposure.

Polllutant	Relationship to Gas Stoves	Health Outcome	Sources
NO2	Created when gas is burned	• Increases asthma symptoms (wheezing, coughing, trouble breathing)Increases asthma symptoms (wheezing, coughing, trouble breathing) • Cause of 12.7% of childhood asthma in the U.S.	• Lebel et al., 2022 • Belanger et al., 2014 • Lin et al., 2013 • Li et al., 2006 • Huangfu & Atkinson, 2020 • Atkinson et al., 2018 • Hasselblad et al., 1992
PM 2.5, PM 10	Created when gas is burned and some is created by cooking itself. This means that while electric stoves produce some PM, gas stoves produce far more.	• Possibly contributes to dementia • Harms cardiovascular system and contributes to stroke, arrhythmia, myocardial infarction (MI), and heart failure • Elevates risk for mortality • Harms respiratory system and causes coughing and wheezing	• Dirgawati et al., 2019 • Sharma et al., 2020 • Simkhovich et al. 2008 • Sharma et al., 2020 • Pope III & Dockery, 1992 • Donaldson et al,. 2001 • Zheng et al., 2010 • Hu et al., 2012
Carbon Monoxide	Created when gas is burned	• Damages respiratory system • Increases cardiovascular morbidity • In high concentrations, causes death through asphyxiation	• Seals and Krasner 2020
Benzene (VOC)	Inertly in gas and produced when burning gas	• Damages immune system • Causes cancer • Increases risk of asthma and exacerbates asthma symptoms • Increased bronchitis symptoms	• Arif & Shah, 2007 • Gordian et al., 2010 • Rumchev et al., 2004 • Billionnet et al., 2011 • Bentayeb et al., 2013 • Lebel et al., 2022
Toluene (VOC)	Inertly in gas and produced when burning gas	• Increases risk of asthma and exacerbates asthma symptoms • Increased bronchitis symptoms • Can be absorbed through the skin from the air	• Arif & Shah, 2007 • Gordian et al., 2010 • Rumchev et al., 2004 • Billionnet et al., 2011 • Bentayeb et al., 2013 • Lebel et al., 2022

Polllutant	Relationship to Gas Stoves	Health Outcome	Sources
Ethylbenzene (VOC)	Inertly in gas and produced when burning gas	• Possibly causes cancer • Increased bronchitis symptoms	• Arif & Shah, 2007 • Gordian et al., 2010 • Rumchev et al., 2004 • Billionnet et al., 2011 • Bentayeb et al., 2013 • Lebel et al., 2022
Xylene (VOC)	Inertly in gas and produced when burning gas	• Increases risk of asthma and exacerbates asthma symptoms • Increased bronchitis symptoms	• Arif & Shah, 2007 • Gordian et al., 2010 • Rumchev et al., 2004 • Billionnet et al., 2011 • Bentayeb et al., 2013 • Lebel et al., 2022
Formaldehyde (VOC)	Produced when burning gas- especially at a simmer	• Increases risk of asthma and exacerbates asthma symptoms • Cancer • Lower Respiratory Infection for Infants	• National Cancer Institute, 2011 • Roda et al., 2011 • Poppendieck and Gong, 2018 • Seals and Krasner, 2020

GAS EQUIPMENT IS SUPPLIED BY FRACKED GAS EXTRACTION

Pollution associated with gas usage inside of homes starts long before its use in gas equipment. Methane gas is a fossil fuel extracted out of the earth, and is composed of 70-90% of methane along with ethane, butane and propane.

The process of getting gas into millions of homes releases dangerous pollutants into the environment.

Pollutants are released from the very beginning of gas discovery and extraction all through its storage, distribution and usage.

Gas extraction with fracking was introduced in the mid-20th century because it allowed drilling in shale reservoir rocks that were previously believed to be too impermeable. The process made gas extraction more economically feasible.

Hydraulic fracturing requires millions of gallons of surface water, an array of chemical additives, and solids (i.e. sand). The water, chemicals, and solids are mixed together, then pumped into the ground under extremely high pressure. This creates fractures in the sediment to release the flow of gas (Madelon et al., 2011).

The technique of fracking threatens public health and environmental health all over the world. Many of the chemicals used to frack are known to cause damage to essential organs such as the lungs, liver, kidneys, and brain (Madelon et al., 2011). These chemicals can and have contaminated nearby air, soil, and water.

The people and animals living and depending on the land, air, and water for survival are put in jeopardy. Most places with drinking wells that are tainted by fracking fluids are in rural and underdeveloped communities, lacking political influence and economic resources (Royte, 2012) to be able to defend their drinking water sources.

An international human rights tribunal on fracking found that fracking violates the right to clean air and water as well as the rights of Indigenous Peoples (Kerns, 2018). The extent of environmental pollution led a number of countries to outlaw the practice of fracking because “the comfort of life is adversely affected” (Holloway et al., 2013), including France, Germany and Spain. However, fracking methane operation occur in 30 U.S. states.

Once the fuel is extracted, it is then refined in order to “clean” the gas and separate out any impurities.

Refineries and petrochemical industries degrade air quality in communities throughout the world by releasing pollutants into the surrounding air, including VOCs (Ragothaman et al., 2017). After the gas is refined, it’s distributed through underground pipelines to reach each consumer.

In the United States, there are 2.56 million miles of gas pipelines transporting fracked gas to more than 75 million consumers (Anderson, 2020). Each pipeline comes with the risk of explosion throughout its construction, maintenance and usage (Peduzzi et al., 2012) (Holloway et al., 2013).

Between 2000 and 2022, the Pipeline and Hazardous Materials Safety Administration (PHMSA), run by the US Department of Transportation, counted a total of 12,782 gas and hazardous liquid pipeline incidents (USDOT, 2022). Of those, 5,804 are considered to be significant incidents.

According to the PHMSA, a significant incident includes: a fatality or injury requiring in-patient hospitalization, $50,000 or more in total costs, a highly volatile liquid release of 5+ barrels or other liquid releases of 50+ barrels, and liquid releases resulting in an unintentional fire or explosion. The potential for explosions, pollution and bodily harm poses a great risk to people living near pipelines. These tend to be rural, lower-income, vulnerable and underserved communities.

METHODOLOGY

EQUIPMENT

To visualize the hydrocarbons and volatile organic compounds (VOCs) released from gas stoves while in use, we used a Forward-Looking InfraRed (FLIR) GF320 camera. The FLIR camera is a portable optical gas imaging camera using infrared technology to visualize by-products of burning fossil fuels.

A FLIR GF320 is typically used by oil and gas industries to detect leaks in infrastructure and facilities.

However, the camera and technology are also equipped to visualize the burning of fossil fuels in homes.

For this study, the FLIR camera was alternated between Auto mode and High Sensitivity Mode (HSM).

Auto mode is an adjustment method that automatically adjusts the image for the best brightness and contrasts to visualize pollutants (Table 3).

In HSM mode the camera's sensitivity allows it to detect heat, which heightens the visual presence of chemicals emitted by combusting fossil fuels.

Red - Fossil Fuels Visible in Auto Mode
Yellow - VOCs Visible in Auto Mode
Blue - Other Gasses Seen in Auto Mode

Methane	Ethane	Propane	Butane	Benzene**
Ethanol	Ethylbenzene	Toluene**	Heptane	Hexane**
Xylene**	Pentane	Methanol	Methyl Isobutyl Ketone (MIBK)	Octane
Methyl Ethyl Ketone (MEK)	Propylene	Isoprene	Ethylene**	

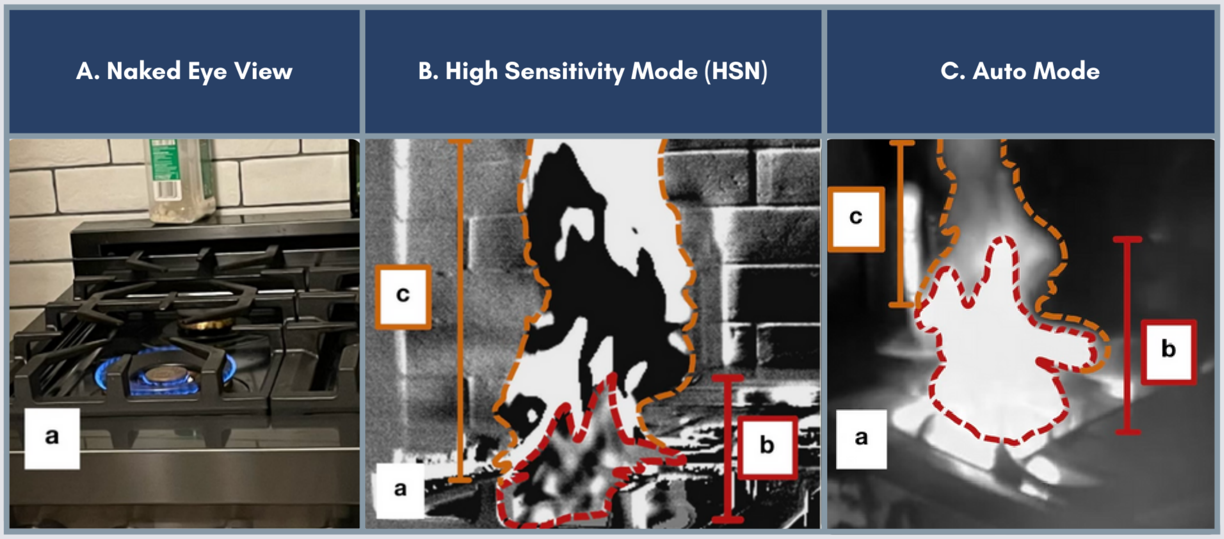
Table. 2.
List of pollutants a Forward-Looking InfraRed (FLIR) GF320 camera can detect in both Auto mode and HSM (Teledyne FLIR, 2023). Highlighted in red are gas hydrocarbons the camera visualizes. Highlighted in yellow are VOCs that the GF 320 can detect and that are commonly found in residential gas.
** indicates status as a Federally Hazardous Air Pollutant (FHAP)

One central question that arose was: "Does the FLIR camera detect pollutants or is it just detecting heat?" The simple explanation is the camera sees both. When gas exits the burner and is lit by a flame, the methane and hydrocarbons break apart, and the combustion releases energy in the form of heat. This generated heat cooks the food on the stove or in the oven, while the atoms released from their methane bonds combine with other atoms around them to form the pollutants NO2, CO, PM, CO2, and more. The by-product pollutants are heated after their new bonds are formed.

Thus the answer to the questions is: The pollution is created by combustion, and it is then heated up and disperses into the kitchen.

The camera observes the entire sequence of chemical transformation. Not all the heated gasses that the camera is showing are dangerous, but the hazardous pollutants are bound up in the other heated gasses and dispersed into the kitchen, dining room, and additional areas of the home. Figure 1 offers a visual explanation of the above description.

Figure 1. Naked Eye and FLIR Camera Views of Gas Stove Flame



(a) cooktop burner, (b) central area of exothermic combustion creating heat to cook and by-product gasses (outlined in dashed red line), (c) plume of by-product gasses emerging from combustion (outlined in dashed orange line).

(A.) Features the gas stove and cooktop burner captured on an iPhone camera. There are no methane fumes or volatile organic compounds visible to the naked eye when the stove is turned on. All that is visible is the blue flame that is used to heat cookware for food preparation.
(B.) Features the gas stove and cooktop burner in HSM captured with a FLIR GF320 camera. Above the intense exothermic combustion outlined in red (b), the camera detects a plume of CO2, NOx, NO2, CO, and VOCs outlined in orange.
(C.) Features the gas stove and cooktop burner in Auto mode captured with a FLIR GF320 camera. The camera's Auto mode shows select VOCs (Benzene, Ethyl Benzene, Hexane, Heptane, Toluene, and Xylene) and
unburned hydrocarbons, outlined in orange, as vapors emerge above the central area of exothermic combustion-- outlined in the red dashed line (b).

FLOW 2 AIR QUALITY MONITOR

To quantify NO_2 and VOC emissions within the indoor air of the study sites, a Flow 2 monitor was used in all 17 locations. Flow 2 has two filters within its design to detect total composition of VOCs and NO_2. The filters are heated up to 250°C to break down the molecules and measure the energy of the molecules.

Flow 2 uses light dispersion and a laser to count fine particles that are in the air. To ensure that the air entering the Flow 2 monitor is the same as its outside environment, there is a 5mm fan spinning at 15,000 rpm inside the device to control the air intake. The small and portable monitor is designed to provide real-time air quality measurements.

CARBON MONOXIDE DETECTOR: CO EXPERTS 2015 MODEL

We used the CO Experts 2015 Carbon Monoxide detector to monitor kitchen and dining rooms for acute increases of carbon monoxide. The monitor does not provide downloadable real time data. Therefore, while we can monitor for increases in carbon monoxide, we can't visualize that data in the same way that we can with the Flow 2.

Additionally, the monitor has a minimum detection limit of 6 ppm, meaning that values less than 6 ppm are recorded as zero. When the monitor exceeds 6 ppm, it makes a short shrill noise and vibrates slowly. When it records values over 15 ppm, it makes a louder noise and vibrates rapidly.

PROCEDURE

Upon entering the house, the FLIR camera was set up on a tripod within eight feet of the stove and pointed toward the burners and the oven door. A Flow 2 monitor was set up on the kitchen counter within 2-3 feet of the stove, and a second Flow 2 monitor was placed on a table in the dining room.

The third monitor was placed by the participant in an area of their choosing, which included bedrooms, 2nd and 3rd floors, and home offices. We placed the carbon monoxide detector next to the kitchen monitor. Then, we recorded a pollution baseline measurement of the home for 5 minutes as we set up the kitchen for cooking.

In each home, we started by preheating the oven. If the oven was gas, the time of preheating was recorded as the start time for cooking with gas.

After 5 minutes of preheating, we started one large gas burner to boil water to cook spaghetti and one small burner to slowly warm up the accompanying sauce. At this time, we began to determine the effectiveness of the vent hood.

We used the FLIR camera to first record footage of the stove burners without the overhead vent on.

When the oven finished preheating, we inserted a tray of vegetables to cook, and we recorded footage of the oven door opening without the vent hood on.

While the vegetables cooked, we turned the vent fan on to full capacity and used the FLIR camera to observe how well the vent captured NO2 and VOC emissions from the stove burners. When the vegetables finished cooking, we turned the vent on, and recorded the vapors coming from the opening oven door before removing the vegetables.

Once the last gas burner or oven was turned off, we recorded that timestamp, and allowed the Flow 2 air monitors to record for an additional 5 minutes.

Throughout the whole process, we observed the carbon monoxide detector. A timestamp was recorded when it exceeded 6 ppm, and we also recorded the highest value displayed by the monitor matched with a timestamp.

RESULTS

HOW TO UNDERSTAND FLIR CAMERA FOOTAGE

The combination of methane and other hydrocarbons with oxygen, plus a spark, produce an exothermic combustion reaction. An exothermic reaction releases stored energy in the form of heat, which heats cookware on the stove.

Some residual heat is also contained in the by-product gasses from the incomplete combustion of hydrocarbons.

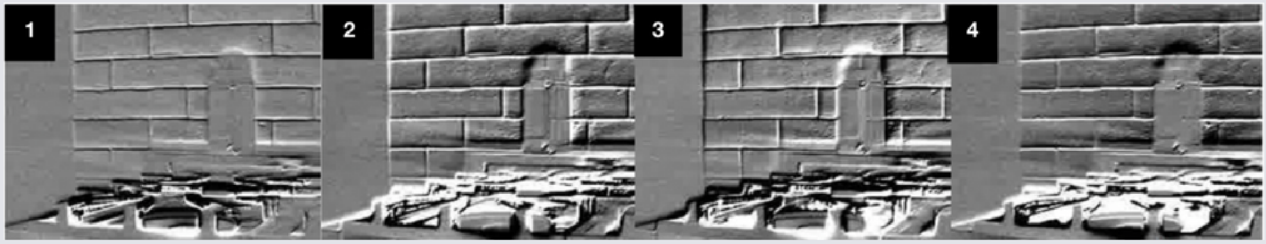
The temperature difference between the by-product gasses and the surroundings, combined with the spectral filter of the FLIR camera allows us to “see” the plume of gasses.

Figures 2 and 3 show frame by frame FLIR footage in HSM mode of a stove burner and oven opening. Beyond Toxics also created a short documentary about this project featuring FLIR Camera footage.

Figure. 2. Frame-by-frame sequence of a FLIR camera video footage showing a chronological process of a stove going from off to on.

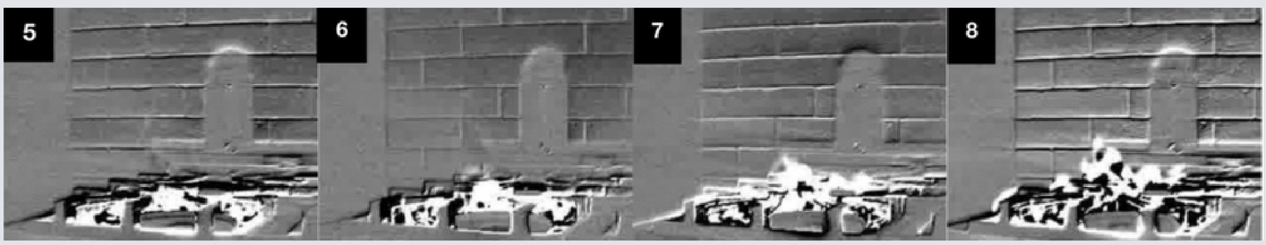
Frames 1-4. There is no methane and hydrocarbon seepage because the stove is turned off.

Stove Off



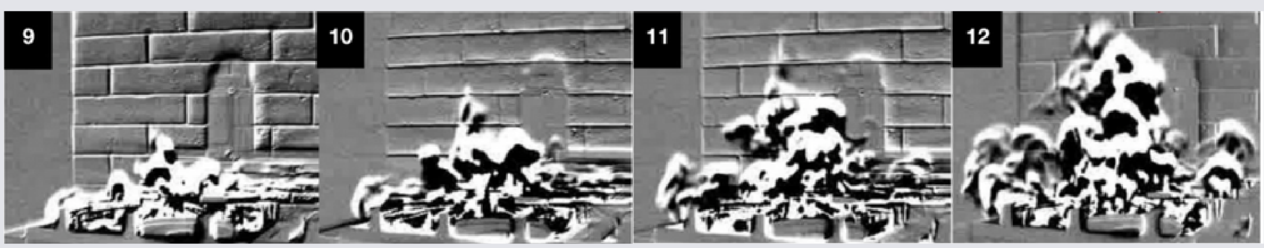
Frames 5-8. When the stove is turned on, we can first see methane and other hydrocarbons seep out of the burner to form a small cloud.

Stove Turned On



Frames 9-12. The methane and hydrocarbons accumulate above the burner to form a taller and wider cloud.

Initial Methane Release Before Ignition

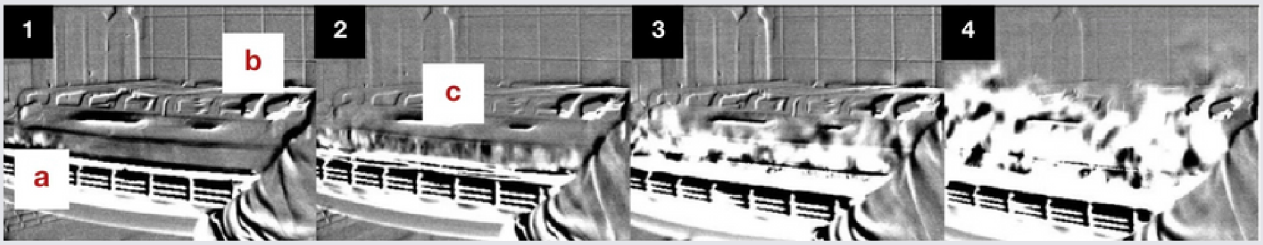


Frames 13-16. The stove's electric ignition spark goes off and ignites the gas to form the blue flame used to cook.

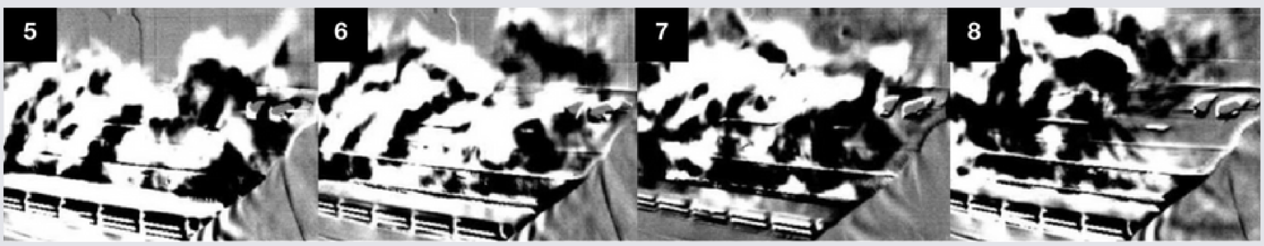
Electric Ignition Spark Ignites Flame

Figure 3 Frame-by-frame HSM FLIR Footage of a preheated oven door opening.

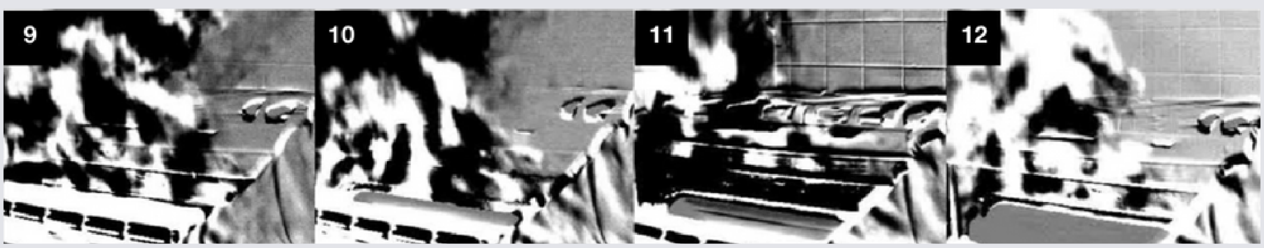
Frame 1. Captured here is an oven preheated to 350°F, (a) depicts the edge of the oven door and the oven handle, (b) depicts the gas stove burners on top of the oven. **(Frame 2)** (c) indicates emissions of CO2, NOx, NO2, CO, and VOCs escaping the oven as soon as the oven door begins to open.



Frames 3-10. Captured in the frames is a growing cloud of pollution leaving the oven and entering the kitchen as the door fully opens.



Frames 11-12. Featured is a shrinking cloud of pollution coming from the oven as the majority has escaped the oven and entered the surrounding area.



VENTILATION RESULTS

This study investigated the efficacy of range vent hoods to remove fumes from the cooking area. The purpose of a range hood is to remove moisture and grease, as well as carbon monoxide, nitrogen dioxide, and other pollutants that cooking using methane gas releases into the indoor living space.

Although some states, like Oregon (Residential Code M1501), may require the installation of a range hood for new construction or remodels, the International Residential Code and the U.S. EPA permits homeowners to voluntarily install a vent hood to capture, filter, and expel the fumes outside through a vent.

Figure 4. Images of ventilation hoods to the ones similar seen in the study

Above are visual examples of the various vents installed in residential homes. Counts of different vent types and their effectiveness at capturing air pollution are discussed in Table 3.

Within the study, all 17 kitchens were equipped with a range hood vent. We encountered five different types of vents. Eleven out of 17 homes were equipped with flat bottom ventilation hoods that had a mesh cover over the vent (Fig. 4A & 4B).

Vents with mesh covers are commonly found under microwaves mounted above stoves, and they have a small surface area. Of these eleven vents, six homes had flat-bottom microwave vents, meaning the vent position was underneath and incorporated into the microwave (Fig. 4A). The surface area of the microwaves and vents did not extend out to cover all the burners. The other five homes were equipped with a dedicated flat bottom vent that extended to the front edge of the stove top and covered a larger surface area (Fig. 4B).

The study also included two industrial-sized hoods (Fig. 4C), one in the shape of a standard rectangle that extends to cover the entire stove, and one in the shape of a trapezoid that did not cover the front corner burners of the stove.

Two downdraft vents were included, one situated on the left side of the burners. The other vent was behind the burners (Fig. 4D). One ventilation duct had no hood or catchment basin (Fig. 4E). Lastly, one household had a flat bottom ventilation hood with two open ducts and no mesh cover.

We used the FLIR camera in order to visualize the flow of gas fumes and see the movement of fumes coming off the gas stoves while in use. There are some factors that could not be analyzed in this study. We did not measure the rate of airflow in the vents, and the vents were not cleaned nor inspected before they were observed. The study thus reflects the everyday ventilation conditions for the participants.

None of the microwave vents (Fig. 4A) succeeded in capturing the fumes from the front burners and they only partially captured the fumes from the back burners. Similarly, non-microwave flat bottom vents with a mesh cover (Fig. 4B) failed to capture all the fumes, especially from the front burners. One of the vents was entirely ineffective because it was designed to release fumes back into the kitchen instead of pulling it outside.

Even though the non-microwave vents extend out further than the microwave vents, the FLIR camera still showed the fumes travel up and past the front of the larger non-microwave before disbursing into the kitchen.

When observing an industrial-sized hood with a rectangular and concave catchment basin that extends over the entire stove, the FLIR camera footage showed there is less fume seepage into the kitchen. However, not all fumes were captured as they rose from the gas stove and oven. The trapezoid-shaped industrial sized hood with a catchment basin that did not extend over the entire stove was ineffective at capturing the fumes from the burners it does not cover.

Downdraft exhaust vents rely on suction power and lack a hood or a catchment basin. Both downdraft vents in the study were situated on different sides of the stoves, one on the left and one in the back. In both cases, the vent pulled in fumes for the two burners closest to the vent. While we could see a change in air movement through the FLIR camera, the downdraft vents could not capture and vent out most of the fumes.

The ventilation duct with no hood or catchment basin was situated directly above the stove in the ceiling. While the vent was off, fumes moved up and around the kitchen. Upon turning the vent on, there was no observable difference in the movement of fumes around the kitchen.

The only vent observed to make a notable difference was a flat bottom ventilation hood with two ducted circular openings. The ducts had no mesh, only cage-like covers with large openings. As soon as the vent was turned on we could see, through the FLIR camera, that the fumes tunneled into the circular ducts, and that there was little fume seepage off the sides of the vent.

We also observed oven emissions through the FLIR camera. We encountered two types of oven vents for releasing emissions: vents above the oven and vents below the oven. Ovens vent out emissions to bring in fresh oxygen in order to sustain the gas flame.

During preheating and cooking, most ovens released fumes through an exit vent located above the oven and behind the back stove burners. The placement of this exit vent allowed the emissions from the oven and the burners to mix together. Due to the fact that oven and stove burner emissions mix together in the space above the range top, ventilation systems that ineffectively vented pollution from the burners were also unable to capture oven emissions.

A few ovens vented emissions from the bottom of the appliance directly below the oven door. Exhaust vents failed to capture pollution exiting from vents located at the bottom of the oven. When oven doors were opened to insert, stir or remove food, none of the vents captured the exiting pollution. We observed the plume of fumes exit into the kitchen because none of the ventilation systems extended out far enough or had strong enough suction capability.

Table 3. Descriptions for the wide variety of ventilation hoods observed in the study. Each hood is characterized by its size, physical attributions and performance.

Archetype	Sub-archetype	Household Quantities	Description of Vent	Description of Results
Flat Bottom Mesh	Microwave	6	Mesh has smaller surface area	High amounts of fume seepage due to lack of extension over the burners and small vent surface area.
	Non-microwave	5	Mesh has larger surface area	High amounts of fume seepage due to lack of extension over the burners
Industrial	Standard Rectangular	1	Large basin that extends over stove burners	Minimal fume seepage off sides due to extended cover of stove burners
	Trapezoid	1	Large basin in trapezoid shape that does not fully cover front burners	High amounts of fume seepage likely due to the shape of hood and lack of extension to the front burners
Downdraft	Suction by fan from a side vent	1	Vent is situated on the counter of the left side of the burners	Minimal, inadequate fume capture due to lack of ventilation hood or catchment basin
	Suction by fan from a back vent	1	Vent is button-activated and located perpendicular to the back of the stove burners	No fume capture due to suction capabilities, lack of hood and catchment basin
Ventilation Duct	No Hood	1	Small circular vent with internal duct located on the ceiling	No fume capture due to suction capabilities, lack of hood and catchment basin
Ducted Flat Bottom	Two ducted vents with no mesh	1	Flat bottom vent with two caged ducts and no mesh	Minimal amount of fumes escaped due to open duct and high airflow in ventilation hood

FLOW 2

NO2 data was interpreted using two measurement systems: Plume Air Quality Index (PAQI) and Parts Per Billion (ppb). Similar to the Airnow Air Quality Index (AQI), created by the EPA and National Oceanic and Atmospheric Administration (NOAA), the Plume Air Quality Index ranks levels of NO2 on a scale of 0-500, with different levels associated with colors and possible health impacts.

This system is designed by Plume Labs and is based on exposure standards set by the World Health Organization.

We also examined the NO2 results in ppb because most researchers use this measurement system when analyzing concentrations of chemicals that may harm health.

This allows us to see which homes had increases in NO2 that researchers have already established as hazardous.

In Table 4, we present the different levels of the Plume Air Quality Index paired with the associated NO2 ppb range to help audiences compare between the two systems.

To interpret data from the Flow 2 monitor, we graphed the data using Python, a common programming language, and the libraries Pandas and Plotnine. Graphs were then overlaid with Plume Labs' Air Quality Index. We also added the time gas started and stopped onto the graph to assist in interpretation. See Figure 5.

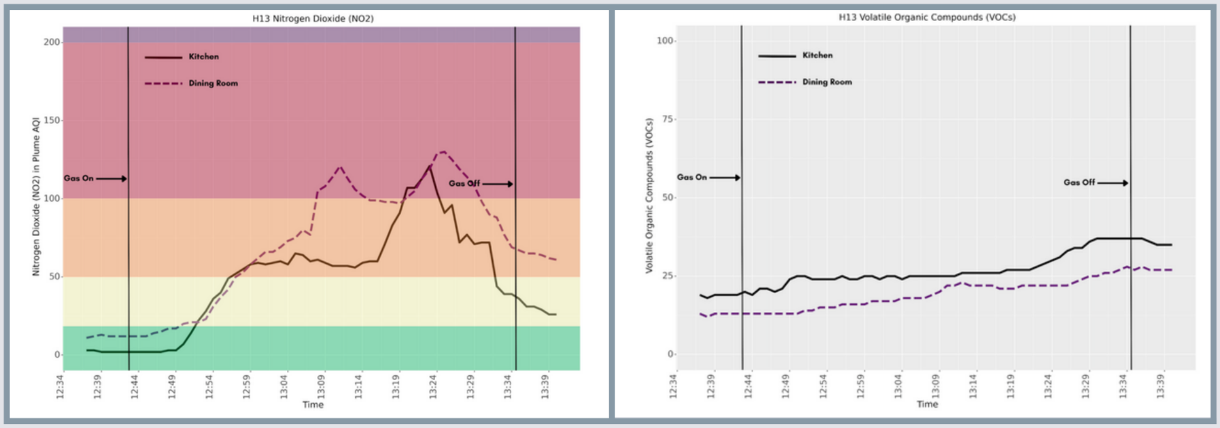
No2 515 + (ppb) PAQI: 200+		Constitutes emergency conditions. Harmful effects can happen to anyone. Avoid any physical activity. Even short-term exposure can be hazardous.
N02: 106 - 315)ppb) PAQI: 101 - 200		Surpasses WHO's hourly exposure limit. Individuals, especially vulnerable populations, likely experience adverse health effects.
NO2: 44 - 106 (ppb) PAQI: 51 - 100		Over WHO's daily exposure limit. Everyone may experience health consequences from prolonged exposure. Sensitive population must take extra precautions.
NO2: 22 - 42 (ppb) PAQI: 51 - 100		Above WHO's annual exposure limit. However, only vulnerable populations are likely to experience health concerns.
NO2: 0 - 21 (ppb) PAQI: 0 - 20		Healthy range. WHO rates this as a safe level of chronic exposure. Ideally, everyone's average exposure stays within this range over a year.

Caption: The left column of the legend features the ppb levels of NO2 with the converted PAQI range values. The middle column features a color assigned to the health exposure thresholds. These colors are used in the graph below to indicate the level of known harm with the level of NO2, measured in ppb, that was measured in each kitchen. Each PAQI range and color is associated with a description. To learn more about Plume's Air Quality Index, visit the PlumeLabs website here.

We did not use the Plume Air Quality Index for VOC graphs because the Flow 2 records the total amount of VOCs in the air, and does not distinguish which types of VOCs are present.

Since different VOCs impact the human body in variable ways, we are unable to speculate on the possible health impacts from measurements of VOCs in the air. Sample graphs for NO2 and VOCs can be found in figure 5.

Figure 5. House 13 NO2 & VOCs



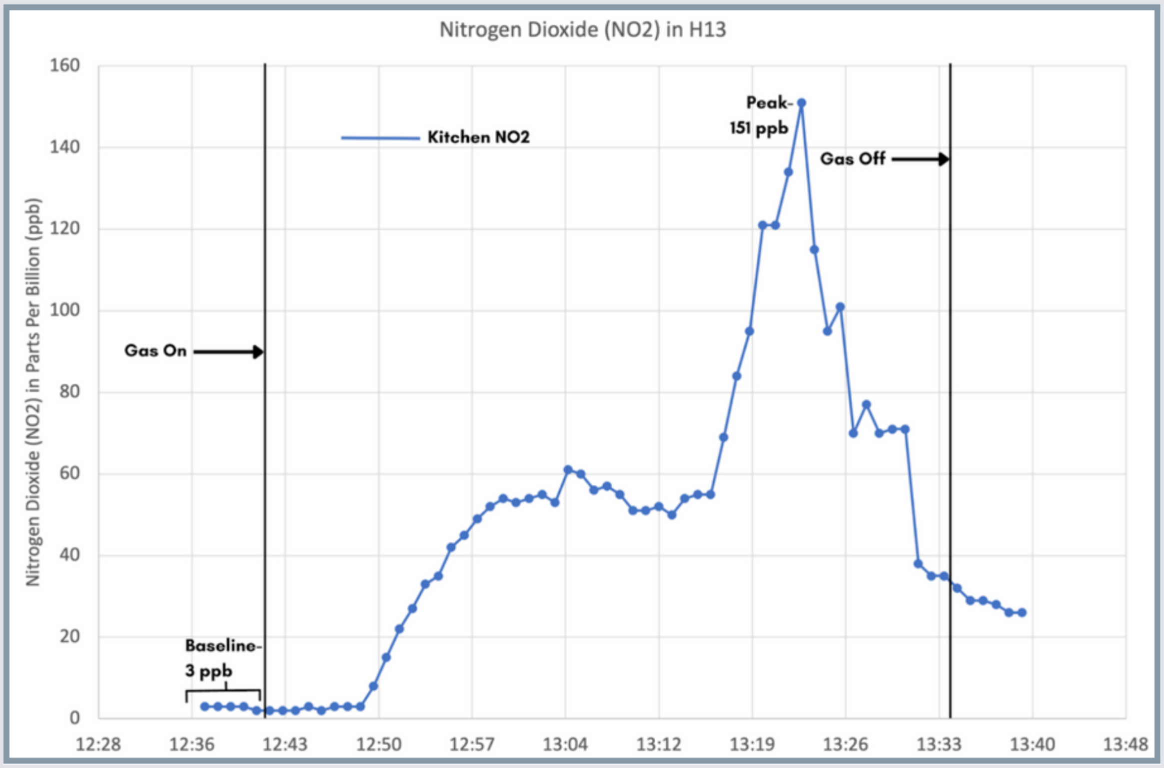
Caption: The first graph shows concentrations of NO2 during the course of cooking at house 13. Prior to cooking the NO2 was in the healthy range (green). After cooking for 10 minutes, the NO2 rose to a level not ideal for vulnerable groups. Ten minutes later, the NO2 became unhealthy for vulnerable groups and not ideal for anyone. Five minutes later, the NO2 reached unhealthy levels for everyone and dangerous levels for vulnerable groups in the dining room. The kitchen also reached unhealthy levels after 5 more minutes. NO2 started to decrease after that, around the time of starting to turn off burners, and continued to decrease after turning off the gas oven marked by the gas off line.

NO2 INCREASES IN PARTS PER BILLION (PPB)

To determine the impact of gas stoves on air quality, we looked at the increase of NO2 or VOCs from the base level of pollution prior to turning on a gas equipment. We averaged the 5 minutes of baseline measurement to establish the background NO2 and VOCs. Then we looked at the highest measurement to establish the peak NO2 or VOC value.

The overall increase is defined as the difference between the baseline and peak. See Figure 6 for an example of NO2 increases. We used the same process for VOC measurements.

Figure 6. Example Baseline, Peak, and Increase of NO2 in House 13



The above graphic shows how we define an increase of NO2 (and VOCs). First, we look at the first 5 minutes of measurements and average them into one number, which in this graph is 3 ppb. Then, we look at the highest measurement of NO2 during the cooking process, which is 151 ppb. The baseline is deducted from the highest measurement which gives us the increase of 148 ppb.

Overall, we found an average increase of 41 ppb of NO2 in kitchens with the smallest increase being 0 and the highest being 148 ppb. We do not think the 0 ppb increase was an error because the dining room also read 0 for NO2, but the 3rd monitor in the ground floor study room did register NO2. For dining rooms, we found an average increase of 42 ppb in NO2 across homes with the lowest increase being 0 and the highest being 157.

VOCs in kitchens increased by an average of 11 ppb ranging from 1 to 29 ppb during the monitoring period. The dining room registered an average increase of 9 ranging from 0 to 35 ppb. We also analyzed the data after excluding air quality measurements in homes with electric ovens.

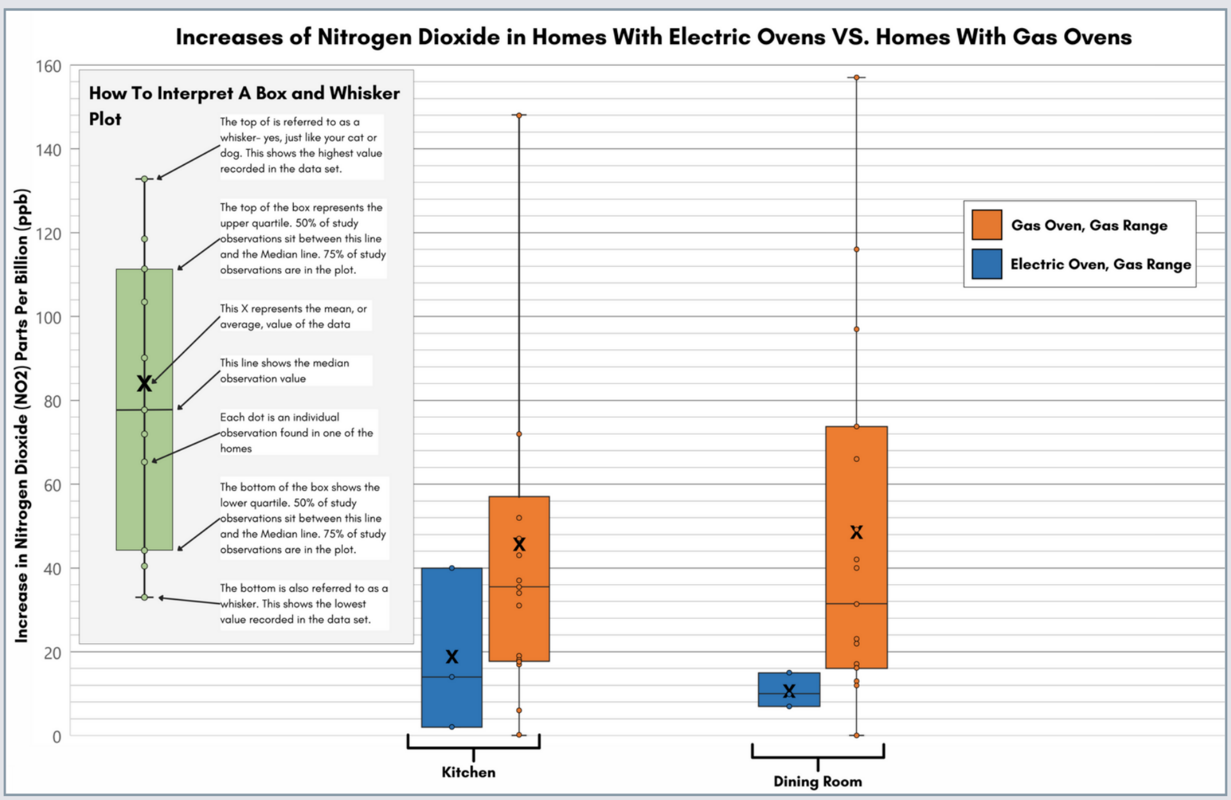
In homes with a gas stove and a gas oven, the average increase of NO2 in kitchens was 46 ppb, while kitchens with an electric oven and gas stove only increased 19 ppb on average. Similarly, kitchens with gas ovens saw a 11 ppb average increase of VOCs in the kitchen while their electric oven counterparts saw a 6 ppb average increase. In dining rooms of homes with gas ovens NO2 measurements rose an average of 48 ppb and VOCs 10 ppb. In dining rooms of homes with electric ovens, NO2 rose an average of 11 ppb and VOCs rose just 4 ppb. These results can be found in Table 5. Homes with gas ovens had higher averages and ranges for both NO2 and VOCs than homes with electric ovens. This is shown on the box and whisker plot in Figure 7.

Table 5. Averages and Ranges of Increases for VOCs and NO2 in participant households separated by electric vs gas stoves.

NO2 Increases in homes with electric ovens	**NO2 Increases in homes with gas ovens**	**VOC Increases in homes with electric ovens**	**VOC Increases in homes with gas ovens**
Kitchen Range: 2-40 ppb Kitchen Average: 19 ppb	Kitchen Range: 0-148 ppb Kitchen Average: 41 ppb	Kitchen Range: 1-9 ppb Kitchen Average: 6 ppb	Kitchen Range: 1-29 ppb Kitchen Average: 11 ppb
Dining Room: 7-15 ppb Dining Average: 11 ppb	Dining Room: 0-157 ppb Dining Average: 48 ppb	Dining Room: 1-9 ppb Dining Average: 4 ppb	Dining Room: 0-35 ppb Dining Average: 9 ppb

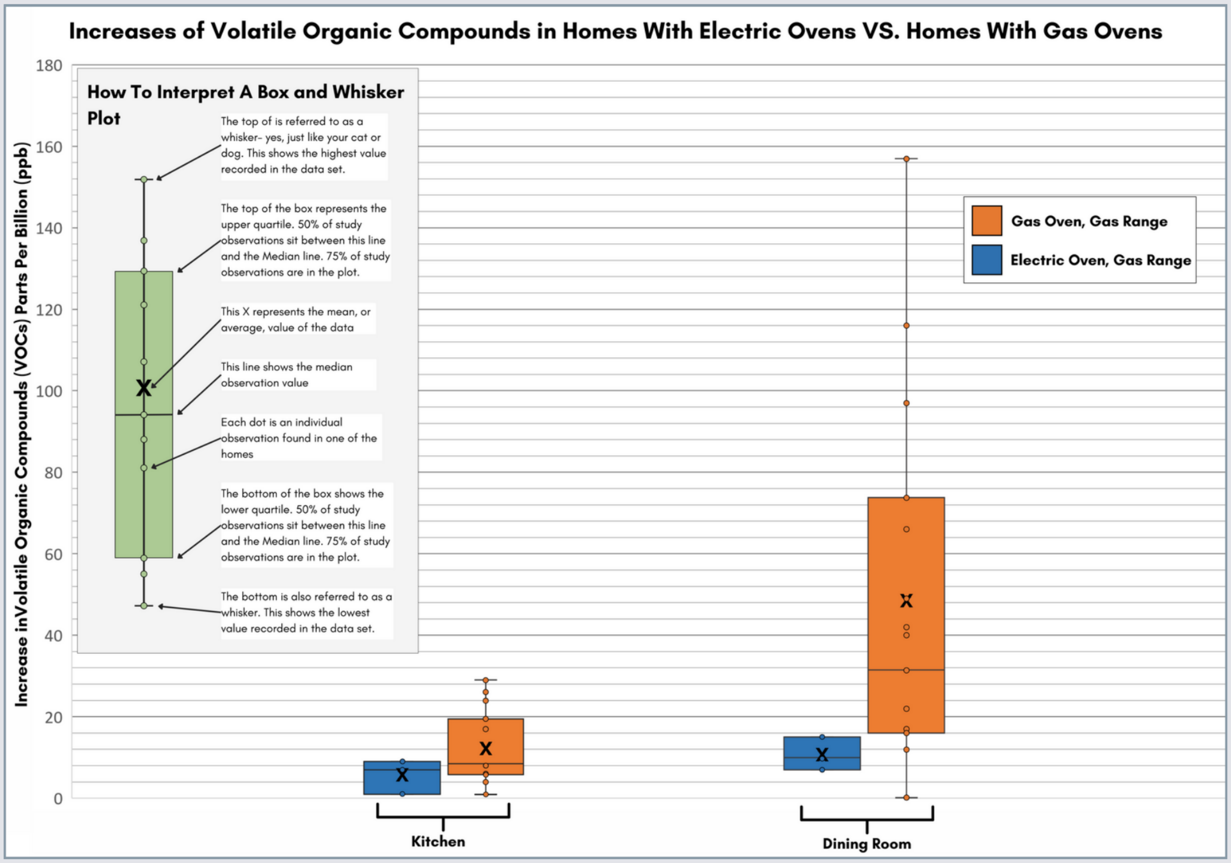
The table features results of NO2 and VOC increases in kitchens and dining rooms separated by homes with an electric vs. gas oven. The results show that homes with gas ovens had far higher emissions of NO2 and VOCs than homes with electric ovens.

Figure 7. Box and Whisker Plot Showing NO2 Increases in Homes with Electric Ovens Vs. Gas Ovens



Caption: The average NO2 increase for households is higher in homes equipped with stoves featuring both gas ranges and gas stoves (orange), compared to homes equipped with stoves using gas ranges and electric stoves (blue).

Figure 7. Box and Whisker Plot Showing NO2 Increases in Homes with Electric Ovens Vs. Gas Ovens



Caption: The average VOC increase for households is higher in homes equipped with stoves featuring both gas ranges and gas stoves (orange), compared to homes equipped with stoves using gas ranges and electric stoves (blue).

CARBON MONOXIDE

For carbon monoxide, 15/17 homes did not have the detector go off meaning those homes stayed under 6 ppm. In house 11, the carbon monoxide alarm went off after 5 minutes of cooking with gas. It peaked at 14 ppm a minute later, and remained around 7 ppm for the rest of the cooking process.

In house 16, the carbon monoxide alarm went off after 30 minutes of cooking with gas. It peaked at 8 ppm, 33 minutes after the oven was turned on, and tapered down slowly after turning off the stove a few minutes later.

DISCUSSION

Our discussion of air monitoring results first details observations of air quality impacts to different areas of the home. We then review the concentrations of air pollutants as related to the current understanding of health impacts, and we also discuss the efficacy of range hood ventilation equipment. We conclude with contextual limitations of data gathered. The most important results of our observations are the measurements of NO2 and VOCs in rooms other than the kitchen.

VENTILATION

The FLIR footage, combined with published scientific research indicates that the type and quality of kitchen ventilation matters. Larger catchment basins, a design that covered the entire cooktop, and higher air flow, all increase the effectiveness of ventilation. However, the households participating in this study rarely had adequate ventilation that effectively captured all the pollution seen through the FLIR camera.

Scientific literature finds that fan speed, hood size, and kitchen size all contribute to variations in NO2 concentrations in residential households (Dobbin et al., 2018; Delp & Singer, 2012). Smaller kitchens often lead to higher NO2 concentrations, presumably because air pollutants accumulate in the small area. Similar to our camera findings, the study notes that small hood catchment areas and hoods that don't cover all burners are less effective at reducing pollutants.

Scientists also found that higher vent speeds cleared air pollution more effectively, which is something not measured in this study.

Another study tested 7 different models of ventilation and found that they capture as little as 15% or less of pollutants and as much as 96% depending on the kitchen setup and model attributes (Delp & Singer, 2012). Even senior officials of the American Gas Association cautioned against the assumption that range hoods would fully solve the problem of exposure to pollution from gas stoves (Leber, 2023).

There is also substantial inconsistency between residential cooking and the use of ventilation according to Sun and Wallace (2021). Those authors found that ventilation hoods were only used for 12% of cooking events. Venting the kitchen by opening a window was used for 15% of cooking events.

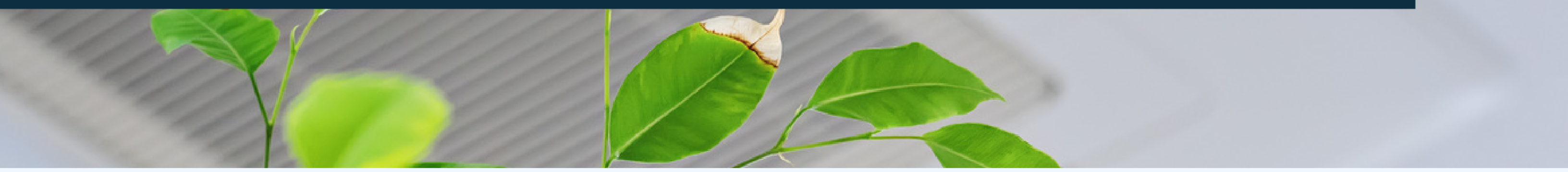
Residents employed a combination of a hood and an open window to create an effective path of ventilation for pollutants in only 2% of cooking events. Cross ventilation created by opening a window was the only means of increasing the effectiveness of flat, typical household ventilation hoods.

Neglecting to use a range ventilation hood when cooking with a gas range is dangerous due to the continuous emission and accumulation of harmful air toxics.

Finally, it must also be noted that using a gas stove with an effective ventilation system including adequate size, airflow, range coverage, and the ability to vent outdoors results in the transfer of indoor air pollution to outdoors. This contributes to smog, ground-level ozone, and toxic outdoor air.

The presence of these pollutants in the atmosphere creates the conditions for climate warming. Thus, the problem of indoor gas stove pollution would not be solved by using ventilation, but merely relocated.

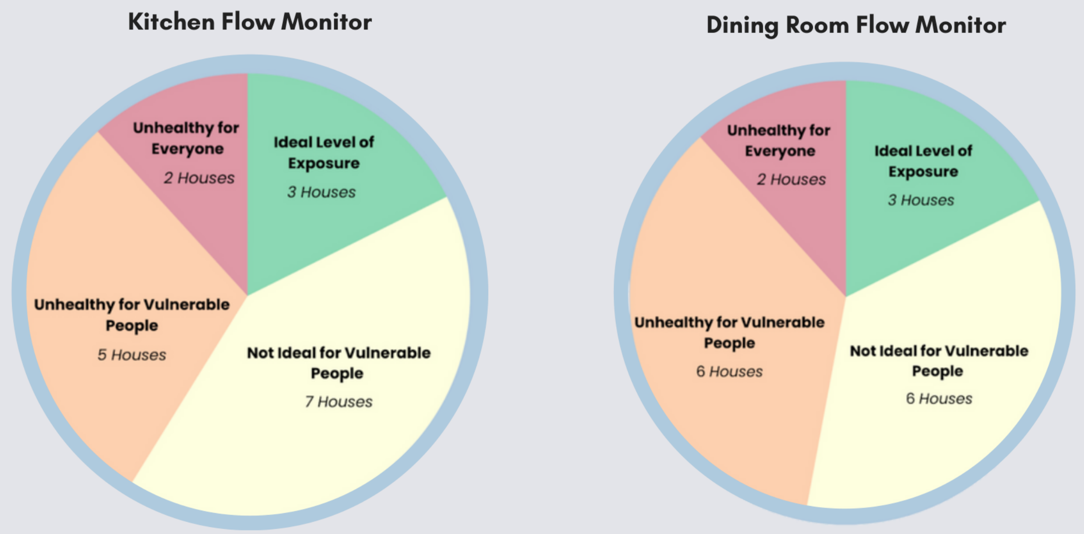
AIR QUALITY DISCUSSION



The data recorded by Flow 2 monitors demonstrates that cooking with gas stoves leads to negative air quality impacts across the home, not just in the kitchen. Figure 8 features two pie charts showing the peak NO2 PAQI color reached in each home.

82% of dining rooms and kitchens reached levels of NO2 that breach the annual chronic exposure limit set by WHO, and many go on to exceed the 1 hour exposure limit by reaching the orange and red levels of the PAQI.

FIGURE 8: Kitchen and Dining Room PAQI Peaks



The two pie charts show how kitchens and dining rooms reached different levels of NO2 exposure. Only 3 kitchens and dining rooms stayed in the ideal level of NO2 exposure (green) while in 15 cases, the air quality was not safe to breathe for some or all household members.. This shows that NO2 travels throughout a variety of home layouts, and dinner guests or family members will be exposed in areas of the homes outside the kitchen.

We offered interested participants the opportunity to place a 3rd monitor in a location of their choice. However, if the home had a second floor, we recommended the monitor be placed in an upstairs room to better understand how NO2 gas might travel throughout homes with multiple floors.

Table 6 breaks down the location of 3rd monitors and the concentration levels based on the Plume Air Quality Index. Seven of 12 homes reached the yellow, orange, and red levels of the Plume Air Quality Index while 5 remained in the green. Figure 9 shows these results in a pie chart for ease of interpretation.

TABLE 6: 3rd Air Quality Monitor Location and PAQI index

Home	Location	PAQI Peak Color
H1	Upstairs Landing	Orange
H2	Ground Floor Bedroom	Orange
H3	Ground Floor Office	Green
H4	Upstairs Landing	Green
H6	Upstairs Landing	Green
H9	3rd Floor Landing	Orange
H10	Upstairs Landing	Orange
H12	Upstairs Landing	Yellow
H13	Ground Floor Bedroom	Red
H15	Upstairs Landing	Green
H16	Upstairs Landing	Yellow
H17	Upstairs Landing	Green

3rd location Flow Monitor

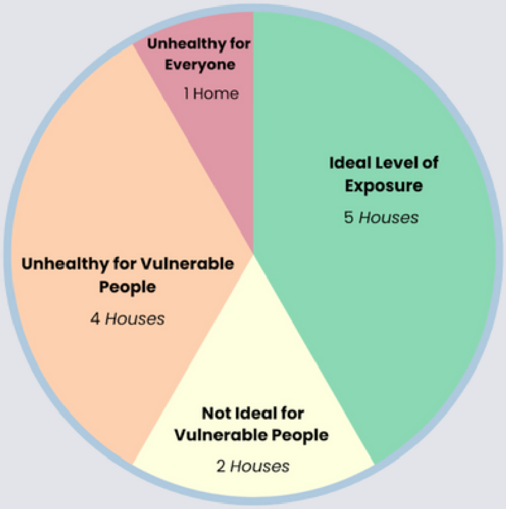


Figure 9: Pie Chart

The 3rd monitor further demonstrates that NO2 travels throughout a variety of home layouts, and dinner guests or family members will be exposed in areas of the homes outside the kitchen. Most of our results are from upstairs landings, which shows that NO2 moves vertically in homes and does not remain confined to the floor where the kitchen is located. Seven of 12 homes demonstrated unhealthy levels of NO2 in third locations primarily including upstairs landings with three of the results, one green, one orange, and one red, pertaining to other ground floor rooms.

We can also examine the NO2 results in parts per billion (ppb), which is useful because even homes that stayed in the green for PAQI displayed NO2 increases shown to cause harm to kids and adults with asthma. Studies have shown that NO2 increases as small as 10 ppb consistently trigger acute coughing, wheezing, and other asthma symptoms for children with asthma (Huangfu & Atkinson, 2020).

In 15 of 17 dining rooms, 14/17 kitchens, and 8/10 upstairs monitors showed a minimum NO2 increase of 10 ppb while cooking.

Researchers also found that increases of 15 ppb or more are enough to increase asthma symptoms in adults, which we saw in 12/17 dining rooms, 12/17 kitchens, and 8/10 upstairs monitors (These results can also be viewed in table 7).

Although homes might stay in the green area of the PAQI index for NO2, residents can still experience exposures significant enough to cause acute negative health impacts for people with previously existing lung conditions.

Finally, it's worth noting that the person cooking is exposed the most to pollution. Stirring pots, opening ovens, and taste tests typically place the cook right over burners where they would breath in the most concentrated pollution.

Table 7.

Standard	Citation	Kitchen Count	Dining Count	Upstairs Count
Increase 10 ppb or more (inflames childhood asthma)	Huangfu & Atkinson, 2020	14/17	15/17	8/10
Increase 15 ppb or more (inflames adult asthma)	Lin et al., 2013; Li et al., 2006	12/17	12/17	8/10

The majority of homes tested showed NO2 increases that researchers claim typically result in an acute exacerbation of asthma symptoms for adults and children.

LIMITATIONS

AIR MONITORING EQUIPMENT LIMITATIONS

The Flow 2 monitor was chosen for its affordability and portability. Recommendations from Plume Labs were followed for calibration, including powering on the device weeks in advance of the study, and also calibrating the AI every day by syncing the Flow 2 with Plume Labs app (Plume Labs, nd).

That being said, Plume notes that the Flow 2s have an accuracy of about 90-95% of static reference monitors. This means our results could be 5-10% off (Plume Labs, nd). The FLIR camera and the carbon monoxide monitor were calibrated prior to shipping to Beyond Toxics.

CONTEXTUAL LIMITS OF AIR MONITORING FINDINGS

Our experiment recorded ambient air quality in a variety of different kitchens with varying ages, brands and models of gas equipment. Our study did not control for size of the kitchen, open vs. closed kitchen floor plans, the rate or efficiency that different stoves burn gas, and the condition of various ventilation models based on operation and maintenance.

It is possible that burners and ovens were not turned on for the same amount of time in each house because the required cooking time differed slightly between households. It is understood that the findings are contextualized within these conditions.

SOLUTIONS & RECOMMENDATIONS

Many participants expressed their shock and dismay upon viewing their gas stoves and ovens through the FLIR camera and visualizing the amount of pollution emitted into their living space from the combustion of fossil fuels inside their home. Our findings add to an already robust literature exemplifying the problematic public health implications of gas equipment in regards to climate change and public health.

While some households have the resources to retrofit a home for electrification, for many others who are renters or who have limited finances, shifting to electric or induction stoves isn't an immediate option. The following section provides a list of precautionary steps to lower long-term exposure to NO2 and VOCs and for home electrification to support the shift away from burning fossil fuels.

ELECTRIFICATION OF NEW CONSTRUCTION

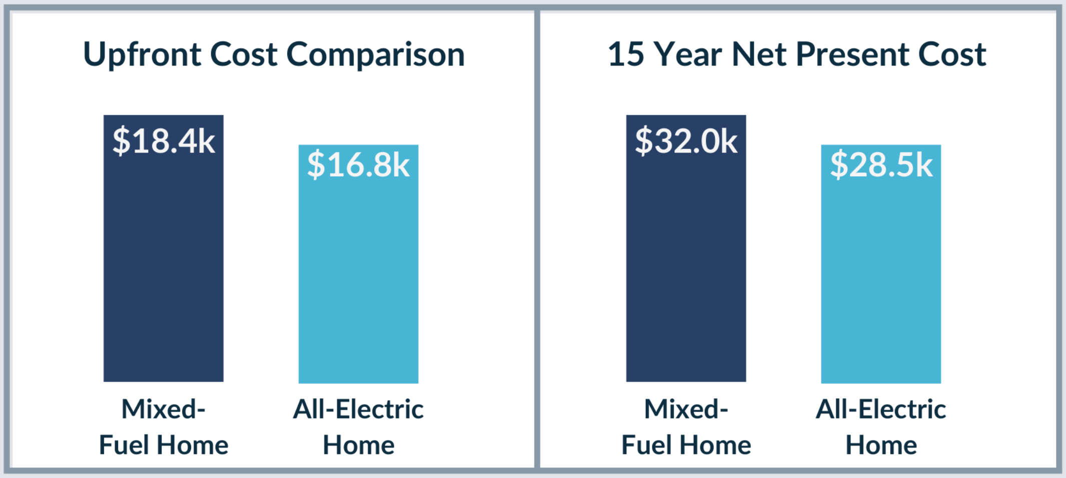
There are many public health benefits to requiring and incentivizing electric equipment in new residential construction. A 2020 Rocky Mountain Institute (RMI) study analyzed all-electric, single-family homes in seven different cities across the country (McKenna et al., 2020), and found constructing all electric homes to be less expensive than mixed gas and electric homes across all seven cities.

An expanded RMI cost analysis found that an all-electric home in Eugene would save $1,600 in initial construction costs, due primarily to the savings from eliminating household gas infrastructure (Fathollahzadeh et al., 2021). Upfront cost savings are also realized because a single appliance—for example, a heat pump—can both heat and cool a home.

In contrast, a mixed-fuel house (i.e., gas and electric) would require two separate appliances: an air-conditioner for cooling and a furnace for heating, which is inefficient and more expensive (Fathollahzadeh et al., 2021).

Electrifying a home originally constructed to run on mixed-gas infrastructure is expensive, which is why it's reasonable to amend building codes by eliminating gas infrastructure in new residential housing. This will save homeowners future renovation costs as gas infrastructure likely becomes obsolete. In addition to upfront construction savings, over the first 15 years, an all-electric home can save $3,500 in net costs, the result of utility bill savings from all electric equipment (Fathollahzadeh et al., 2021).

Figure. 10. RMI Costs for Constructing Mixed Fuel vs All-Electric Homes in Eugene



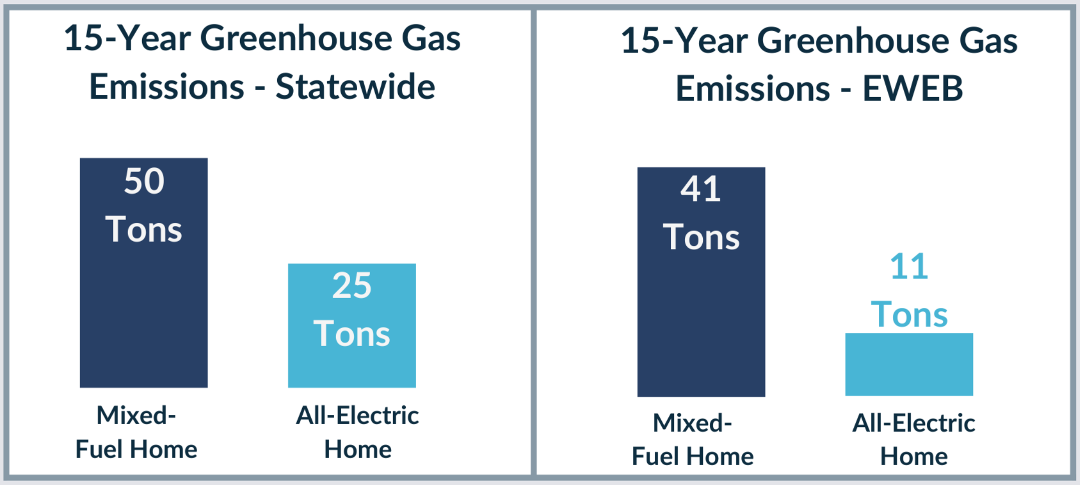
This graph shows the upfront and 15 year net costs for Mixed Fuel (dark blue) vs All electric homes (light blue). Original graphic made by RMI (Kocher, 2022)

GHG EMISSIONS SAVINGS

Using the Eugene Water Electric Board's 2021 published data on GHG emissions intensity, the emissions reduction for an all-electric home was 74%, a reduction of 30 metric tons of CO2 over a 15-year period. (Kocher, 2022)

Our recommendations include taking advantage of the inherent carbon reduction and cost savings of all-electric construction. Given this, switching from fossil fuels to electricity in residences can help reduce carbon emissions, lower health risks from methane, and save upfront construction costs.

Figure. 11. Emissions Savings for an All-Electric Home vs Mixed-Fuel Home in Eugene



This graph shows the 15 year carbon emissions for Mixed Fuel (dark blue) vs All Electric homes (light blue). The left figure shows Oregon wide average emissions while the right figure shows average emissions for Eugene Water and Electric Board customers. Original graphic made by RMI (Kocher, 2022).

ELECTRIFYING YOUR EXISTING HOME

Residents may want to replace their gas cooking and heating equipment with high efficiency electric systems as they approach time for replacement, or for repairs when the equipment breaks down. They can use government incentives from the Inflation Reduction Act, local governments, and utilities to lower the cost.

If household members are prone to respiratory diseases such as asthma or chronic bronchitis, replacing gas stoves sooner, if possible, and/or increasing ventilation, is strongly advised.

MONEY FROM THE GOVERNMENT IS AVAILABLE TO HELP PEOPLE SWITCH FROM GAS TO ELECTRIC

The Inflation Reduction Act (IRA) has rebates of up to $14,000 available for low and moderate income households to help electrify home heating systems, increase insulation, and lower power bills. This includes an $840 rebate for switching gas stoves to an all-electric alternative. For home heating systems, the IRA has incentives for heat pumps to heat and cool the air and incentives for heat pump water heaters to replace older heat waters.

Heat Pumps and Heat Pump Water Heaters are very efficient which makes them cheaper to run than gas or traditional electric heating systems and can save people money on energy bills. The IRA also includes rebates for a new electric panel and wiring to install electric equipment, such as adding 240 V outlets for electric stoves and clothes dryers.

CONSIDER INDUCTION COOKING WHEN SWITCHING FROM GAS

When upgrading from gas to electric cooking systems, consider trying an induction oven or cooktop. New induction ovens and cooktops boil water in half the time of traditional gas and electric cooktops by using magnets to heat the pot or pan while using less energy. Induction cooktops are also available as countertop units that use a traditional wall outlet without requiring a 240 V outlet (which must be installed by a licensed electrician).

These countertop units are relatively inexpensive and can be used to supplement or replace gas cooking (without needing to remove an existing stove) while also being faster than gas or other electric cooktops.

FOR RENTERS

Renters may be concerned about investing in new electric equipment because moving equipment between rentals or getting a landlord's permission can be cumbersome. However, there are all-electric alternatives you can take with you when relocating that don’t require any new wiring or renovations.

For cooking, there are new countertop induction cooktops that run on a traditional wall outlet and can be taken with you when moving. There are also new portable heat pumps available for heating and cooling designed to fit in a window and run off a traditional outlet (Gradient Comfort).

Figure. 12. Window Heat Pump (left) and a Countertop Induction Cooktop (right)

INCREASE KITCHEN VENTILATION

If you have ventilation hoods, get in the habit of using them. Prioritize cooking on the back burners which are usually positioned under the hood to take advantage of the exhaust capture. Immediately turn on the hood vent when using any burner as opposed to waiting until smelling cooking odors or seeing smoke.

Keep the vent on for a few minutes after cooking to capture any slower moving particles. Opening a window can create more effective air flow for moving pollutants into a hood and dilute the concentration of pollution inside the home.

If you don't have a ventilation system in your house, consider setting up two box fans in a window during temperate months. One box fan should be set up to bring in fresh, outdoor air, and the other should be set up to move indoor air outdoors. This will help cycle the pollution outside of your house.

Additionally, HEPA (high efficiency particulate air) and carbon filter equipped air purifiers have been found to reduce NO_2 and other air pollutants from gas stoves (Paulin et al., 2014).

CONCLUSION

Gas stoves in residential homes expose residents to toxic airborne nitrogen dioxide, volatile organic compounds, and carbon monoxide. In the process of dispersing gas stove pollutants into the outside environment through exhaust vents and windows, gas-powered equipment contributes to the global accumulation of greenhouse gasses responsible for climate change.

Using an air quality monitor, we found acutely hazardous or chronically risky concentrations of nitrogen dioxide in 82% of the homes within our study.

We also found that 94% of the homes lacked ventilation systems that could effectively capture stove emissions, and none that could capture oven emissions.

We recommend supporting local and state building code amendments that incentivize the installation of all-electric equipment in new residential construction. If gas stoves cannot be replaced in the near term, electric appliances such as plug-in induction units, electric tea kettles and plug-in crock pots can reduce the use of gas while also reducing emissions of toxic air pollutants during some cooking tasks.

We also recommend that individuals seek opportunities to replace gas-powered equipment with all-electric alternatives using available local, state, and federal funding. These actions will result in saving money, reducing climate impacts, and increasing safety within homes.

ADDITIONAL RESOURCES

Making informed decisions about home energy upgrades will become easier as a result of current and upcoming state and federal funding programs. In some cases, whole home retrofits for low-income households or help with upfront costs for moderate income households may soon become available

See a list of electric stoves for less than $840 lower income households can get for free here:

Electric Stoves You Can Get for Free With the IRA Rebate (lifehacker.com)
See the full list of Inflation Reduction Act Incentives, and find out which you may be eligible here:

How much money can you get with the Inflation Reduction Act? — Rewiring America

You may also be eligible for incentives from your local utility that can be combined with Inflation Reduction Act Incentives to maximize benefits for your household. Work with contractors that can help connect you with these local and Federal Incentives. See local incentives from the Eugene Water and Electric Board here.

Example: Incentives are available from the Inflation Reduction Act and the Eugene Water and Electric Board for low-income customers. These incentives could potentially be combined to pay for higher cost upgrades or to pay for a greater percentage of the total costs of upgrades, and possibly make the upgrades free for low-income customers.

	Federal Inflation Reduction Act Rebates (<80% Area Median Income)	**EWEB Incentives for Low-Income Customers (<200% Federal Poverty Level)**
Heat Pump	$8000	$3800 (ductless)
Heat Pump Water Heater	$1750	$800
Heat Pump Dryer	$840	N/A
Weatherization	$1600	100% of insulation costs, some of windows and doors
Wiring	$2500	N/A
Electric Panel	$4000	$5000
Electric Stove	$840	N/A
Total	up to $14000	$9600

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