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Ten questions concerning building electrification

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ABSTRACT

Building electrification is the movement to shift building operational energy use from fossil fuels toward electricity. It has been pursued mainly to reduce greenhouse gas (GHG) emissions from the building sector. We present here ten questions concerning building electrification and attempt to answer them in the context of the existing literature. Our questions span dimensions of policy, life cycle impacts on energy and environment, technological advances and challenges, indoor and outdoor air quality, health, economics, and social-behavioral factors. We find that while much of the extant research predicts that building electrification will provide benefits in terms of GHG emissions, pollutant exposures, and economic impacts, it remains limited to a narrow set of geographic regions and typically fails to capture the full extent of life cycle environmental impacts. Additionally, despite logical inferences for likely health benefits, we were unable to identify explicit studies of the health impacts of building electrification. We also find a common theme that, for building electrification to be successful in reducing GHG emissions, costs, and adverse grid impacts, it should be approached in parallel with increased building energy efficiency, grid renewable power, and smart grid infrastructure. Finally, we find that people hold strong opinions about fuel options in their homes, and the relationship between preferences and energy use is complicated. To shift people's beliefs around electrification, government-originating communications can highlight the benefits, but one must still account for heterogeneous household conditions. We conclude by suggesting key research areas needed to approach building electrification effectively and equitably.

1. Introduction

Building electrification encompasses the shifting of buildings' on-site combustion of fuels – primarily natural gas but also oil, propane, and wood for space heating, water heating, cooking, and other end-uses – towards electric appliances and equipment. While electrification is being promoted, overarching questions and concerns for widespread building electrification remain, including but not limited to the evolving policy landscape, the impacts of electrification on energy production, consumption, and climate, the stability and reliability of the electric grid, impacts on air quality and health, upfront and operational costs, disparities in the electrical readiness of existing buildings, equitable access to technologies, and end-user acceptability of such transitions [1,2]. In this work, we attempt to address these concerns in the context of the existing literature through ten structured questions. Notably, we broaden the extant research by examining the connections between building electrification and indoor air quality via cooking emissions, as cooking is a dominant source of indoor pollutants, before delving into the potential health impacts of building electrification. Our focus is primarily on the U.S. and Canada given our expertise concerning building electrification policies and infrastructure in these two countries, but we supplement with literature pertaining to other countries where useful.

2. Questions

2.1. Question 1: Why is building electrification being promoted and pursued?

Building electrification has long been identified as a key strategy for reducing greenhouse gas (GHG) emissions from the building sector [3], and it is being heavily pursued and promoted in global, national, and local efforts to curb climate change [4]. Building electrification is also motivated by efforts to improve the health and well-being of building occupants, especially in residential settings, as fossil fuel appliances for heating and cooking can increase indoor pollutant concentrations and

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contribute to adverse health outcomes [5–8]. Furthermore, as the electric grid undergoes a transition towards cleaner energy sources, and as renewable sources and storage capacities continue to become more cost-competitive in the U.S. and Canada, building electrification is now a viable strategy to reduce long-term operational costs for both building owners and occupants [4,9,10]. In spite of policies and incentives promoting decarbonization, which will take decades, mid-term pathways must account for the coexistence of fossil fuel-based energy systems with the simultaneous emergence of new carbon-neutral energy systems [11]. For example, in the U.S. Department of Energy's (DOE) April 2024 national blueprint for decarbonizing the building sector, the goal is to reduce GHG emissions from U.S. buildings by 65 % by 2035 and 90 % by 2050 compared to 2005 levels, achievable through a combination of increasing building energy efficiency, accelerating on-site emissions reductions, transforming the grid, and minimizing embodied life cycle emissions [12].

2.2. *Question 2: What is the policy landscape for promoting building electrification?*

In both the U.S. and Canada, the recent policy shift towards building electrification has been facilitated by updated codes, policies, funding initiatives, guidelines, and technological advancements. Such changes are not isolated to specific geographic areas, and we note that, since Berkeley, California became the first city to ban natural gas in new construction in 2019, several jurisdictions across the United States and Canada have begun promoting building electrification [13–15]. Many of these areas are introducing or plan to introduce all-electric "reach" codes, which exceed mandatory state code requirements and require new building construction and/or existing building retrofits to effectively eliminate the use of fossil fuels. However, the movement has not been without challenges. For instance, the U.S. Court of Appeals for the Ninth Circuit overturned the gas ban in Berkeley in April 2023, and the city agreed to repeal the ordinance in March 2024 [16,17]. The Canadian government also recently created a carve-out to delay their federal carbon tax from being applied to homes fueled by heating oil for three years [18]. Similarly, Local Law 97 in New York City recently provided good-faith effort exemptions to provide more time to meet the city's climate goals [19]. Preemptive legislation aiming to prohibit natural gas bans has also been introduced in more than 20 U.S. states [20].

The most significant push for building electrification in the U.S. came in 2022 with a $370 billion commitment from the nationwide Inflation Reduction Act (IRA) to support the transition toward clean energy [21], which includes promotion of decarbonization of the electric grid and electrifying the building stock [22]. Specifically, the IRA directs funding towards incentivizing various electrification measures, such as the installation of electric heat pumps, induction cooktops, and rooftop solar panels [23]. The IRA also provides resources, including $10 billion in funding and tax credits, to deploy building electrification strategies for multi-family residential buildings, including federally assisted housing through the Green and Resilient Retrofit Program established by the U.S. Department of Housing and Urban Development (HUD). Additionally, it provides $1 billion in funding for the DOE to fund grants to state and local governments to adopt updated building energy codes, including zero-energy codes, and provides $27 billion to establish the Greenhouse Gas Reduction Fund, administered by the U.S. Environmental Protection Agency (EPA), to catalyze investment in clean energy projects to decarbonize communities across the U.S [24]. To address socioeconomic inequalities and promote environmental justice, which are barriers to the effective implementation of the IRA [25], the Act offers additional rebates and tax credits for projects located in economically distressed communities, traditional energy communities, and native communities.

In Canada, there are also various policies and incentive programs available at the federal, provincial, and territorial levels to promote the use of clean energy and enhance energy efficiency in homes [26]. For example, the Canada Greener Homes Grant Initiative, launched in 2021, promotes home improvement through professional pre- and post-retrofit evaluation [27]. To make funding more accessible, specific programs that target clean energy projects within Indigenous, rural, and remote communities were also created [28]. Echoing developments in the U.S., Canada has also implemented programs and allocated funds to expedite the advancement of technology for building and large-scale electrification [10].

Integral to the aforementioned policy initiatives is funding for research and development into technologies to facilitate the transition towards affordable and accessible building electrification and clean, renewable energy. This includes investments in clean hydrogen research, which is considered carbon neutral and a potential substitute for fossil fuels [29]. The U.S. Government has recently initiated significant research funding for hydrogen through the Hydrogen Shot program, which establishes Regional Clean Hydrogen Hubs [30]. As well, research is being supported for the development of advanced heat pump systems with efficiency at a wide range of operating temperatures [31]. To this end, the U.S. Government invoked the Defense Production Act in 2022 to facilitate the production of five key technologies, including heat pumps, to achieve national climate goals [32]. We acknowledge that complete building electrification will result in substantial increases in winter electrical demand, even shifting the grid from peaking in summer to peaking in winter in many locations [33], and we explore such impacts in Questions 4 and 9. In addition, there are barriers to integrating renewable energy into the grid, particularly increases in capacity that require new transmission lines [34]. Thus, building upgrades for improved energy efficiency as well as long-term electricity storage are important complements to electrification retrofits if increases in electricity demand are to be met [35].

Related to these policies and funding initiatives, green building standards and certification programs also promote the electrification of both residential and commercial buildings, reflecting the building industry's efforts to advance building electrification to meet climate goals. Programs such as LEED and BREEAM allocate credits specifically towards energy performance and the integration of low- or zero-carbon technologies to reduce GHG emissions from buildings [36,37]. In 2022, ASHRAE's Task Force on Decarbonization published a *Position Document on Building Decarbonization*, committing to eliminating GHG emissions from the built environment and supporting "beneficial" electrification of heating systems [38,39]. Other examples include the Redwood Energy Guide, tailored for both single-family and multifamily residences, which has gained traction, particularly in California [40], and the Residential Energy Services Network (RESNET) Carbon Rating Index, which aims to provide an accurate metric to quantify GHG emissions when energy is used in a home [41].

2.3. *Question 3: What are the energy and climate impacts of building electrification?*

Buildings account for about one-third of global energy consumption and about one-quarter of global carbon dioxide (CO_2) emissions [42]. In the U.S., buildings account for about 40 % of total primary energy consumption [43] and about 35 % of total GHG emissions [44]. Nationally, residential and commercial buildings rely heavily on electricity to meet end-use energy demands, with approximately 65–70 % of their GHG emissions attributable to electricity use and the remaining GHG emissions attributable to the direct consumption of natural gas and, in smaller amounts, petroleum for space heating, water heating, and cooking.

The use of natural gas and other fossil fuels in buildings contributes to GHG emissions not only through CO_2 emissions resulting from their combustion but also through the release of methane (CH_4), a potent GHG with high global warming potential (GWP), both as a product of incomplete combustion in exhaust gases and through the release of unburned gas through leaks from piping, fittings, and appliances and equipment such as furnaces, water heaters, ovens, and some stove burners (e.g., those with pilot lights) [45–47]. Therefore, in principle, building electrification with increasingly cleaner electricity sources will reduce GHG emissions, both by reducing the amount of CO_2 emitted by fossil fuel combustion and by reducing the amount of methane that is released both from combustion and leakage. However, building electrification will also introduce greater amounts of vapor-compression refrigeration equipment (e.g., heat pumps) to convert fossil fuel appliances and equipment to electric, which can have adverse climate impacts by increasing fugitive emissions of refrigerants with high GWP [48]. The magnitude of lifecycle GHG impacts of appliance replacement will vary depending on the refrigerant that is being used, the timing of equipment replacement (e.g., early replacement versus waiting until the end of life), the magnitude of embodied energy in new equipment, and how waste from replaced equipment is managed [49].

A number of recent studies have projected the energy, economic, and environmental impacts of relevant electrification policies and/or specific technologies on GHG emissions, with varying depth and breadth of scope in considering the above-mentioned factors. Williams et al. [50] used high-level models of infrastructure and electricity systems to demonstrate that widespread electrification of buildings, transportation, and other sectors would need to be combined with energy efficiency and decarbonized energy supplies to meet GHG emission goals in California [50]. Steinberg et al. [51] used power sector modeling to estimate that electrification of vehicles, industries, and buildings coupled with power sector decarbonization could reduce economy-wide emissions of CO_2 associated with fossil fuel combustion by nearly 75 % in 2050 relative to 2005 levels, and that electrification of these sectors alone could still achieve emissions reductions of approximately 41 % (with transportation accounting for the majority [~63 %] of GHG reductions and buildings accounting for ~31 % of this amount) [51]. Similarly, Langevin et al. [52] found that widespread building electrification, energy efficiency improvements, and increased connections of building-based renewables to the grid could reduce CO_2 emissions from the U.S. building stock by as much as 80 % by 2050 [52].

Bistline et al. [53] modeled the impacts of the IRA on economy-wide GHG emissions, comparing outputs from nine different economy-wide models of energy supply and demand, and projected GHG emissions reductions of 43–48 % below 2005 levels by 2035 [53]. The study noted that buildings already account for the most electricity usage among all end-use sectors in the U.S. and that their share will increase over time under IRA provisions due to electrification. Thus, any projected emissions savings are intricately linked to the rate of simultaneous emissions reductions from the power sector.

Heat pumps for air and water heating are a critical technology for achieving widespread electrification [54]. Currently, the rate of heat pump installation in the U.S. is about 13.6 %, which is higher than the global rate of 10 %, while the number of heat pump installations in colder climates such as Canada is about 5.3 % [55–57]. This suggests that our current rate of electrification is not yet sufficient to meet near-term climate goals, amplifying the importance of the aforementioned policy measures (Question 2). Additionally, while the capacity and efficiency of ground- and water-source heat pumps are relatively stable over time regardless of ambient air temperatures (since ground and water temperatures are relatively stable, depending on depth), both the capacity and efficiency of air-source heat pumps can vary substantially with ambient temperatures [58]. Newer air-source technologies are capable of providing coefficients of performance (COP) in heating mode of at least ~2 at ambient temperatures as low as −25 °C to as much as ~6 at higher temperatures (e.g., up to ~10 °C), although supplemental heating through electric resistance heating or other means may be necessary at extremely cold conditions to meet heating demands [59, 60]. Thus, in-situ performance – in terms of both delivered capacity and operational efficiency – over the duration of a heating season is critical for determining the net impact of air-source heat pumps on GHG emissions relative to gas or other fossil fuel combustion equipment used for space heating.

As an example, Manjarres and Dusault [61] compared a 96 % annual fuel utilization efficiency (AFUE) gas furnace to an electric air-source heat pump with a seasonal COP of 3.8 for residential heating applications in Illinois with current grid GHG emissions factors, including both average and marginal conversion factors for electricity from natural gas plants. While the electric heat pump revealed lower site energy use, it had ~30 % higher source energy use and GHG emissions [61]. Even an 80 % AFUE gas furnace was estimated to yield ~10 % lower GHG emissions than the electric air-source heat pump. Higher source energy estimates are attributable to higher source-to-site energy conversion factors for electricity compared to direct use of natural gas in the region, and the higher GHG emissions estimate is attributable to the grid in Illinois being relatively dirty because of its >60 % fossil fuel base [62]. Thus, a rapid approach to building electrification in Illinois without concurrent decarbonization of the electric grid would actually lead to higher air pollution and associated health burdens than the current baseline. Conversely, in a location like Ontario where coal generation has been phased out and nuclear and hydroelectric power plants contribute significantly, electrification via heat pumps would immediately reduce energy consumption and GHG emissions [63].

While these results do not account for the climate impacts of methane leakage from natural gas or refrigerant leakage from the increased prevalence of heat pumps, they do emphasize how, at least in some climates and geographic locations, the potential for building electrification to lead to decreases in GHG emissions from fossil fuel combustion is dependent upon concurrent decarbonization of the electric grid. When compared to electric resistance heating with a COP of ~1, natural gas appliances and equipment are even more favorable concerning both source energy use and GHG emissions [64]. The opposite would be true in locations with a cleaner grid, favoring electrification.

Deetjen et al. [65] estimated that 70 % of U.S. homes could reduce GHG emissions by installing heat pumps to meet their heating needs; however, while they did account for a reduction in methane leakage in natural gas infrastructure, they did not account for increases in refrigerant leakage from increased use of heat pumps, which likely overestimates the GHG emissions reductions [65]. Walker et al. [66] investigated the GHG impacts (e.g., change in CO_2-equivalent emissions) of meeting home heating loads when switching from a natural gas furnace to a heat pump for the mainland U.S., finding that GHG savings are readily achievable by transitioning to heat pump technologies for the vast majority of homes, albeit with significant installation costs (see Question 8 herein), and that the COP required to achieve carbon and energy cost neutrality varies by a factor of four across the U.S. because of the variability in CO_2-equivalent content of electricity and electricity-natural gas price differences [66]. Their analysis assumed that the change to heat pumps would be instantaneous, and projections were thus based on current, not future, energy prices and fuel/grid emission factors. The study also excluded the effects of both refrigerant and methane leakage on the climate, but the authors did cite a UK study estimating that the refrigerant loss for operational domestic heat pumps is about 3.5 %; however, when a leak occurs, the median refrigerant loss is about 35 % of the initial refrigerant mass [67]. This suggests that heat pumps have a greater net GWP than many have previously considered due to leakage. Similarly, end-to-end methane leakage from natural gas must be accounted for, as it increases the GWP of both types of heating systems, albeit within different boundaries. For example, methane leakage associated with natural gas furnaces can occur both through the appliance as well as throughout natural gas distribution networks, whereas, for electric heat pumps, leakage occurs only in distribution networks that terminate at power plants.

In what is arguably one of the most extensive studies to date of the climate impacts of residential heat pumps, Pistochini et al. [68] forecasted the GHG emissions of electrifying space heating in U.S. homes. All known GHG emissions sources associated with gas furnaces and heat pumps were considered, including long-term end-use marginal CO_2

emissions from electricity generation, CO_2 emissions from natural gas combustion, and fugitive methane and refrigerant emissions from leaks over both 20-year and 100-year timescales [68]. The forecasts utilized two prototype home models with current weather files and varying electricity generation mixes, assuming an annualized average refrigerant leakage of 7.5 % and an 80 % reduction in refrigerant leakage every 5 years (per the American Innovation and Manufacturing Act's environmental and hydrofluorocarbons reductions targets). The authors of this particular study projected population-weighted U.S. average emission reductions of 53–67 % in 20-year GWP for a heat pump compared to a gas furnace. As comprehensive as this work is, it is sensitive to many assumptions. For example, a recent research project published by ASHRAE highlighted the importance of inspecting for refrigerant leakage in constructed building-level refrigerant systems, as the study found about 33 % of the tested compression fittings and 56 % of the flare fittings had initial leak observations, with the level of a technician's expertise positively correlating with the leak rate [69,70]. While these limitations are reasonable and even necessary to yield projections within inevitable constraints and uncertainties, opportunities remain to integrate variability in these factors into projections of life cycle climate impacts using a holistic integrated framework that expands the types of homes/buildings investigated, accounts for future climate changes, and explores the impacts of different scenarios of electricity generation mixes.

The energy and climate impacts of fuels for other end uses such as water heating and cooking have generally been studied in less depth. For water heating, which represents around 10 % of residential energy consumption in the U.S., a 2015 study estimated that gas water heaters have lower primary energy consumption and CO_2 emissions than traditional electric water heaters [71]. A 2016 study estimated that the GWP of a heat pump water heater would be lower than conventional natural gas/electric tank or tankless water heaters, and that the amount of methane leakage was the most important factor governing the climate impact of gas-fueled technologies [72]. Others have noted that heat pump water heaters assisted by solar collectors would further reduce GHG emissions [73]. The EPA has recently updated the phase-down of hydrofluorocarbons by imposing a GWP of less than 700 for any new systems that need to be charged after January 1, 2025 (i.e., GWP of R-410a is 2088) [74]. The current goal for the U.S. DOE is to develop new heat pumps for space conditioning and water heating that can operate with refrigerants that have a GWP of 10 or less [75]. These refrigerants usually require modifications of the system to account for the operation of the heat pump and flammability of these refrigerants (e.g., R-290 with a GWP of 3).

Regarding cooking, which accounts for only ~3 % of residential site natural gas energy consumption [76] and less than ~2 % of residential site electricity consumption [77], but still generates significant public and policy interest (i.e, see Question 9), it is estimated that electric induction cooktops are 5–10 % more efficient in transferring energy than conventional electric resistance cooktops and about three times more efficient than natural gas cooktops [78], although others note that other factors also impact efficiency, such as the size of cooking vessel used [79]. One study of annual household cooking energy consumption in Korea compared end-use data from a zero-energy housing complex using induction cooktops to a sample of households that used natural gas for cooking and found that induction cooktops consumed less than half as much primary energy and emitted about 40 % of the GHGs compared to natural gas cooking [80]. The primary energy and climate impacts of induction, electric resistance, or gas stoves will, of course, depend on the local electricity generation mix.

Combining space conditioning, water heating, and cooking, a recent study on residential new construction conducted by the Rocky Mountain Institute (RMI) found that, across nine U.S. cities, a fully electrified home with a multi-zone air source heat pump for heating and cooling, a hybrid electric heat pump water heater, and an induction cooktop and electric oven have lower lifetime GHG emissions. This is true even when indirect emissions from both methane and refrigerant leaks are accounted for, when compared to new mixed-fuel homes with a high-efficiency gas furnace, centralized air conditioner, gas water heater, and gas cooktop and oven [81]. While the embodied energy of these appliances may not have been accounted for, this research highlights the projected positive climate impacts of new fully electric homes.

2.4. Question 4: What is the likely impact of building electrification on building and grid infrastructure resilience?

Building electrification is expected to increase electricity demand, even when considering parallel improvements in building energy efficiency, which will in turn necessitate an increase in the total capacity of the electric grid as well as adjustments in flexibility requirements to meet different magnitudes and timings of electricity demand outside of conventional summer peaks. For example, a study focusing on building electrification in California estimated that, while heating electrification was projected to lead to a 30–40 % reduction in GHG emissions in 2050, it would require significant increases in grid resource capacity “due to the higher magnitude of load increases and lack of readily available renewable generation during the times when electrified heating loads occurred” [82]. Similarly, the installation of photovoltaic (photovoltaic (PV) panels and the grid load could lead to challenges such as the ‘duck curve’ which shows the transition point to solar energy [83]. A study focused on heating demand in British Columbia predicted that a full heat pump transition would modestly increase annual electricity consumption (by 19 %) but would lead to an outsized (37 %) increase in peak electricity demand and a shift from summer to winter peaks [84]. How such peaks match with the timing and magnitude of electricity production with high penetration of renewables will vary widely by geographic location, among other factors. Moreover, such changes in both total and peak demand will necessitate a variety of other strategies to improve load matching such as battery and thermal storage, vehicle-to-grid integration, and smart grid controls, as well as increased energy efficiency [85–87]. Hybrid systems that combine heat pumps with gas furnaces or boiler backups could also reduce winter peaks [88].

Grid resilience and reliability are important both from a system level and at the level of individual buildings because of the adverse impacts that outages can have on individuals, especially during extreme weather conditions. Adverse outcomes from power outages can escalate to the point where buildings cannot maintain their core functionality to provide critical life support and ultimately endanger occupants. Notable events include the 1995 heat wave in Chicago that killed more than 500 people [89], and the February 2021 extreme cold snap from the migration of the polar vortex that disabled most of Texas' power grid and left many people without heat [90]. While a major contributor to the power outages in Texas was the deregulation of the power sector, which allowed natural gas suppliers to bypass winterizing their operations for cold weather [91], the magnitude of impacts of the outages on the ability of buildings to provide heat to occupants was likely amplified by the fact that Texas and other hot-climate states have a much higher proportion of homes with electric heat than colder-climate states in the north. For example, over 70 % of homes in the DOE's hot-humid climate region rely on electricity as their primary source of space heating, compared to fewer than 25 % of homes in the cold/very-cold region [92]. In a region with predominantly gas heating, where electricity demands for heating during peak heating periods are needed only to power fans and pumps while space heating is provided by natural gas combustion in furnaces and boilers, the peak demand on the grid would be lower than that of a region with a high proportion of electric heating and, thus, gas heating can help make the electric grid more resilient. Additionally, the reliance on primarily above-ground power lines to distribute electricity poses an additional risk for power outages, especially during extreme weather conditions, whereas underground natural gas distribution networks are less affected [93]. Extreme weather also impacts the production from renewables to the grid, such as reducing PV output during snow cover where it coincides with the heating demand for the electrified systems [94].

Conversely, the polar vortex migration in early 2019, like prior polar vortices, did not have the same drastic effects on heating outages in northern states, likely due to stricter regulations on the power sector but also possibly due to the greater reliance on natural gas for heating rather than electricity. For example, the electric grid remained resilient in states such as Illinois in part because its nuclear and, to a lesser extent, its coal plants typically operate with a 90-day supply of power during cold weather [95,96]. However, threats to grid reliability in Illinois and other states with heavy reliance on nuclear power could increase as their nuclear plants reach their planned retirement dates (most of the U.S. nuclear plants were built in the mid-20th century). Ultimately, buildings need to ensure they maintain the provision of essential services to remain survivable for occupants during a power grid failure, especially with the projected increases in demand on the electric grid driven by electrification. In a broader context, the latest Intergovernmental Panel on Climate Change (IPCC) report predicts future climate extremes in every region around the world [97]. In just the past summer, the electric grids of a number of states in the U.S. were close to their extreme peak operation. In recent years, the probability of electric grid outages due to wildfires has also increased [98,99], suggesting an all-electric building connected only to the grid could be less resilient in these extreme events. Similarly in recent years, such as December 2022, cold days led to more notices from the electric grid providers to encourage lower setpoint temperatures for electricity conservation if health permits [100]. Given the recent impact of climate change and extreme weather conditions, the consideration of operating the electric grid under these conditions with electrified buildings is a major active focus area of technical and policy research.

2.5. *Question 5: What are the indoor and outdoor air quality impacts of building electrification?*

Numerous studies have characterized emissions of airborne pollutants associated with natural gas appliances used for cooking, space heating, water heating, and other purposes (e.g., Ref. [5–7,101–103]). These emissions include a range of pollutants, such as particulate matter (PM), carbon monoxide (CO), formaldehyde (HCHO), sulphur dioxide (SO_2), and nitrogen oxides (NO_x). Through simulation, Logue et al. [104] estimated that occupant exposures to NO_2, CO, and HCHO levels resulting from residential natural gas cooking burners without venting range hoods routinely exceed acute health-based standards and guidelines [104].

Many studies have quantified the emissions of indoor pollutants from cooking using gas appliances. Wallace et al. [5] reported that the use of gas stove burners or gas ovens, even in the absence of food, could emit ultrafine particles (UFP) with a diameter of 100 nm or less at a rate of 4 × 10^{12}/min or higher [5]. Farmer et al. [105] observed an increase in CO and NO_x concentrations when a gas stove or oven was in use in a test home, with NO_x concentrations reaching levels comparable to the acute (1-h) National Ambient Air Quality Standards (NAAQS) of 100 ppb, especially during extensive cooking activities such as Thanksgiving meal preparation [105]. Furthermore, even when the gas stove/oven was not in use, indoor NO_x concentrations were typically higher than those outdoors, likely due to the emission from the stove and oven pilot lights. This finding is supported by a prior investigation on the impact of energy retrofit in low-income apartments, which found that replacing gas stoves with a standing pilot light with those having electronic ignition, in addition to the presence of vented range hoods and increases in ventilation rates, reduced the average indoor NO_2 concentrations by 58 % in five apartments [106]. The indoor air quality impacts of pilot lights were also quantified by a study of seven single-family homes in California, which found that the continuous combustion of pilot lights contributed to elevated ultrafine particle, CO, and CO_2 concentrations [107]. Similarly, Patel et al. [108] estimated a mass emission rate of ultrafine particles of 0.9 ± 0.2 μg/min and a number emission rate of sub-10 nm particles of $1.6 \pm 0.6 \times 10^{12}$ # particles/min from a pilot light in the same test house as Farmer et al. [105]. For these reasons, a reasonable short-term recommendation, regardless of electrification status, would be to replace pilot lights with electronic ignition, in combination with other indoor air quality mitigation strategies.

In addition, formaldehyde, which is a known human carcinogen, can be generated from the natural gas combustion that occurs during cooking activities. An interesting characteristic of formaldehyde emission rates is their negative association with increased gas flow rates, which is in contrast to particle number emission rates that tend to increase with higher temperature and flame output [101,103,109]. For this reason, simmering with low flame output could result in an elevated concentration of formaldehyde exceeding the acute Reference Exposure Level (REL) of 55 μg/m^3, established by the California Office of Environmental Health Hazard Assessment (OEHHA) [110]. A recent study also confirmed high emission rates of benzene (2.8–6.5 μg/min) when gas or propane stoves/ovens are used at levels 10–25 times higher than those of electric stoves [111]. These emissions can result in benzene concentrations exceeding the OEHHA acute REL of 27 μg/m^3.

Moreover, it is worth noting that emissions generated from cooking activities do not remain solely in the kitchen space. In a study of nine California homes, Singer et al. [6] found that the use of gas stoves and oven burners for scripted cooking not only resulted in significant increases in CO_2, NO_x, and particle number concentrations within home kitchens but also led to elevated pollutant concentrations in bedrooms, particularly in apartments and homes with open floor plans. Moreover, although pollutant concentrations declined after cooking concluded, they remained elevated above background levels for several hours. This trend aligns with observations from other studies that monitored daily pollutant concentration changes in residences [112,113]. Another investigation also confirmed that formaldehyde can easily travel to the living room when the kitchen door is open even in closed-concept Chinese kitchens [103]. This suggests that building occupants, even outside the kitchen space, are still exposed to cooking-related pollutants during and after cooking activities.

Recent studies also suggested that fugitive leaks from natural gas appliances for cooking and heating when they are not in use could be an underappreciated source of hazardous air pollutants, particularly benzene, toluene, ethylbenzene, and total xylenes (BTEX). However, the fraction of leaks contributing to indoor pollutant concentrations and occupant exposure remains unclear [114]. By collecting natural gas samples from 159 unique residential stoves in California and applying previously established methane emission rates, Lebel et al. [7] estimated a statewide benzene emission rate from homes. Using this estimation in a modeling analysis, the authors found that the median benzene emission rate would lead to concentrations below the OEHHA chronic REL of 3 μg/m^3. However, if benzene emissions are extremely high and homes are extremely airtight (this combination is rare but not impossible), it can result in indoor benzene surpassing the OEHHA chronic REL. This finding suggests the need for more comprehensive assessments to quantify the impact and address the uncertainties associated with fugitive natural gas leaks on indoor air quality.

Given the high pollutant emissions from gas appliances used for cooking, it is evident that there should be indoor air quality benefits associated with the electrification of cooking appliances. In a randomized study evaluating the efficacy of various interventions to reduce NO_2 concentrations in homes with unvented gas stoves, Paulin et al. [115] found that replacing unvented gas stoves with electric stoves led to a significant reduction in median NO_2 concentrations, with a 51 % decrease in kitchens and 42 % in bedrooms [115]. However, it is also important to note that pollutant emissions from cooking – especially fine PM, which is considered the predominant contributor to adverse health outcomes of indoor air pollutants in residences – also originate from the food itself in addition to the heating source [101,116–118]. Therefore, electrification alone only addresses a fraction of the pollutants associated with cooking fuel and other mitigation strategies are needed (such as exhaust ventilation) to further address pollutant emissions from cooking, regardless of fuel source. This point is further explored in Question 6.

Beyond cooking, air pollutants can also originate from combustion heating appliances, such as furnaces, space heaters, water heaters, and fireplaces. Among these, unvented appliances are the most concerning, as all the combustion fumes containing harmful air pollutants and water vapor are directly exhausted into the space where the appliance is located. An early study of two homes in Colorado identified unvented natural gas fireplaces as significant indoor sources of CO, NO_2, and polycyclic aromatic hydrocarbons (PAHs), and found that using an unvented fireplace for just 2 h could result in CO concentrations exceeding 100 ppm [119]. A study of 30 homes in the U.S. with unvented gas fireplaces found that health-based standards and guidelines were exceeded for CO in 20 % of homes and for NO_2 in most homes [120]. A study of 16 homes in Chile found that homes with unvented combustion space heaters using compressed natural gas, liquefied petroleum gas (LPG), or kerosene had higher PM, UFP, and NO_2 concentrations than those with electric heaters or central heating [121]. Due to the substantial emissions associated with indoor unvented combustion heating devices, they cannot be sold in California [122], but they are still permitted in most other U.S. states as well as Canada. The 2020 ASHRAE *Position Document on Unvented Combustion Devices and Indoor Air Quality* recommends that “users [of unvented combustion devices] should properly operate unvented appliances installed in the home” and that “[c]onsumers who want to reduce the risk of adverse health effects due to exposure to combustion products should not use unvented appliances” [123].

Vented gas combustion appliances generally have a smaller impact on indoor air quality because their fumes are directly exhausted outdoors. However, similar to cooking appliances, the continuous combustion of pilot lights in heating appliances contributes to elevated pollutant concentrations, such as NO_x, when compared to homes without them [102]. Furthermore, back-drafting and combustion gas spillage due to depressurization could lead to increased concentrations of CO and NO_2 [124]. In comparison to natural gas appliances, biomass combustion appliances could have even worse impacts on indoor air quality. While biomass is considered a renewable resource, and high-efficiency biomass appliances are encouraged through tax credits, both the indoor and outdoor environmental impacts associated with biomass burning extend beyond GHG emissions [78,125,126]. For example, an Italian study found that open wood-burning fireplaces, although vented, can result in a median combustion-to-background concentration ratio of 4 and significantly contribute to the risk of lung cancer [127]. While closed fireplaces and pellet stoves have smaller impacts, they still elevate the median background particle concentration by a factor of two.

Vented combustion appliances also impact outdoor air quality through their exhaust. For instance, Zhu et al. [128] estimated that gas appliances from residential buildings emitted approximately 15,900 tons of NO_x and 12,000 tons of CO in California in 2018, which could be substantially reduced through electrification. A simulation study in California further confirmed the air quality benefits of electrification and found that electrifying residential and commercial buildings contributes to a reduction of up to 5 $\mu g/m^3$ in ambient $PM_{2.5}$ in winter, primarily achieved by replacing residential wood combustion for heating with clean electric heating [129]. This reduction in ambient $PM_{2.5}$ concentrations would, in turn, contribute to lower indoor background concentrations while improving air quality, especially in regions where biomass combustion appliances are commonly used.

Overall, building electrification is expected to reduce indoor pollutant emissions from fuel combustion and reduce ambient pollutant concentrations, which, in turn, could also improve indoor air quality. However, certain data gaps remain. Given that many existing studies primarily focus on the impact of electrification on outdoor air quality at scale, there is a need to understand how the indoor and outdoor air quality impacts of electrification interventions vary depending on pollutant type, building characteristics, and occupant behaviors. The literature on cooking emissions and factors that influence the strength of emission sources may provide some valuable insights into addressing these questions, which are further explored in Question 6.

2.6. *Question 6: Could building electrification substantially reduce emissions from daily cooking activities?*

Many studies have reported that the airborne pollutant emission rates during cooking activities are influenced by fuel type (e.g., natural gas versus electricity), cooking appliance type (e.g., stove, oven, or microwave), cooking method (e.g., water-based, frying-based, or dry cooking), cooking temperature, and the specific food ingredients being prepared (e.g., Ref. [118,130]). While it can be challenging to establish a consistent relationship between these factors and the magnitude of cooking emissions due to differences in test setups, measurement and reporting methods, and variability in replicate measurements, some general trends can be identified from these studies. Notably, regular use of a range hood also has significant beneficial impacts on the indoor pollutant concentrations that result from cooking emissions.

In the U.S. and Canada, natural gas and electricity are the predominant cooking fuels for both cooktops and ovens [131]. A useful way to compare the impact of these cooking fuels on indoor air quality is by examining emissions when no food is being cooked. As discussed in Question 5, a substantial amount of gas-phase pollutants, including CO, NO_x, formaldehyde, and benzene, can be emitted from natural gas combustion during cooking activities [103,105,106,111]. Additionally, a wide size range of particles, some as small as a few nanometers in diameter, are also generated by combustion [5,108]. When compared to natural gas stoves, electric resistance stoves perform better in terms of gas-phase pollutant emissions (e.g., NO_2) because of the elimination of the combustion process [132]. However, a substantial amount of particles can still be emitted from high-temperature electrical heating elements. For instance, Wallace et al. [5] reported that when no food was cooked, the UFPs that were emitted from the electrical coil were generally larger in diameter but had overlapping distributions compared to gas stoves (geometric mean diameter of 3.2–22 nm vs. 4–7 nm) with a comparable range of emission rates for electric stoves ($0.6–11 \times 10^{12}$/min) and for gas stoves ($4.6–13 \times 10^{12}$/min) [5]. In a 2015 study of an electric burner, Wallace et al. further suggested that the particles could be generated from the desorption of organic compounds sorbed to the burner and cookware from indoor air [133]. Patel et al. [108] observed that particle number emissions resulting from naked heat sources (i.e., without food) were dominated by sub-10 nm particles for both a gas stove and an electric hot plate, but the gas stove emitted nearly an order of magnitude more sub-10 nm particles than the electric hot plate ($2.4 \pm 0.3 \times 10^{14}$ # particles/min vs. $4 \pm 2 \times 10^{13}$ # particles/min), and also nearly an order of magnitude more 10–100 nm particles ($2 \pm 1 \times 10^{12}$ # particles/min vs. $4 \pm 2 \times 10^{11}$ # particles/min) [108]. Compared to cooktops, both gas and electric ovens have similar emission rates when no food is cooked ($0.3–5.1 \times 10^{12}$/min for gas vs $3.1–6.4 \times 10^{12}$/min for electric), although electric ovens have 2 to 3 times higher peak concentrations of particles between 2 and 64 nm compared to gas ovens [5].

Compared to electric resistance stoves, induction stoves are relatively newer cooking appliances that are often marketed as a cleaner cooking option and have been increasingly promoted and adopted [23]. However, there have been very limited investigations into particle emissions from cooking on induction stoves, except one recent study showing that the mean personal $PM_{2.5}$ exposure in urban Ecuadorian households randomized to induction stoves was 11 $\mu g/m^3$ lower than those using LPG stoves [134]. Also worth noting is the fact that induction stoves reduce cooking time for the same dish by 16.7–74.8 % when compared to an LPG stove, and 55.8–94.4 % compared to an electric resistance stove [135]. This reduction in cooking time can help reduce the concentration of pollutants that accumulate during cooking. However, further research is needed to quantify the particle emissions from induction stoves in other settings and assess their full benefits on indoor air quality.

When food is being cooked, the distinction in particle emission rates between gas and electric cooking becomes less evident due to the influence of other cooking-related factors. For instance, Hu et al. [136] synthesized $PM_{2.5}$ emission data from 13 measurement studies and revealed overlapping distributions of emission rates for gas and electric cooking, likely because the emissions from food masked the differences between cooking fuels [136]. The only exception was microwave cooking, which had a mean emission rate two orders of magnitude lower. When considering cooking types, frying and grilling also exhibited overlapping $PM_{2.5}$ mass emission distributions, while cooking in ovens had emissions lower by two orders of magnitude [136]. Similar overlaps were observed for different food and oil types.

Gas stoves have been shown to result in UFP concentrations that are 2–14 times higher than electric stoves for cooking activities such as boiling water, stir-frying, deep-frying, and baking [101,109,132]. However, one study reported slightly lower (80–100 %) peak UFP concentrations from gas grills compared to electric grills when making toast and bacon [132]. Frying-based methods such as deep-frying, stir-frying, and pan-frying, as well as dry cooking methods such as grilling and toasting, generally result in higher emission rates or concentrations of ultrafine particles [109,137,138]. In contrast, water-based cooking such as steaming and boiling generally have about an order of magnitude lower UFP emission rates compared to frying-based methods. When considering the impact of temperature, studies by Zhang et al. [109] and Buonanno et al. [101] found that higher heating power output resulted in 1.7–3 times higher concentrations or emission rates of UFPs [101,109]. Lastly, regarding food and oil types, fatty foods tend to have slightly higher UFP emission rates, while oils with high smoke points generally have lower emission rates [101,139].

In a cross-study comparison, Audignon-Durand et al. [130] summarized 30 cooking studies with 163 particle number concentration measurements and found that the average peak concentration resulting from a single mode of cooking method was the highest for frying ($2.68 \times 10^5/cm^3$), followed by grilling ($2.68 \times 10^5/cm^3$), toasting ($1.95 \times 10^5/cm^3$), boiling ($1.25 \times 10^5/cm^3$), oven baking ($1.18 \times 10^5/cm^3$), stir-frying ($0.84 \times 10^5/cm^3$), and pan-cooking ($0.73 \times 10^5/cm^3$) [130]. However, it is important to note that the variations within each cooking method, such as frying (ranging from $0.03–22.1 \times 10^5/cm^3$), are much greater than the differences between cooking methods. These variations are expected due to a combination of differences in testing setups, space volumes, measurement locations, and cooking methods, which makes it challenging to predict occupants' exposure to UFP concentrations resulting from a single cooking activity in a specific residence and the influence that fuel type may have on that exposure.

Another factor that significantly influences indoor pollutant concentrations resulting from cooking emissions is the use of a kitchen range hood. Studies have demonstrated that cooking-related pollutants can be mitigated through the use of an adequately sized vented range hood, which can effectively reduce the concentration of pollutants generated from cooking activities by up to 90 % through direct removal at the source and with an increased ventilation rate [6,103,110,140,141]. Yet, many homes lack a functioning vented range hood, and residents in homes equipped with an adequately sized range hood meeting airflow requirements might opt to not use it during cooking activities due to noise, lack of awareness regarding the harm of indoor pollutants or benefits of ventilation, energy costs, or other concerns [142–144]. Indeed, multiple studies have reported that in North America, at least two-thirds of occupants choose not to regularly use a range hood or open windows during cooking activities [131,144–146]. This trend might explain why the installation of vented hoods did not significantly reduce indoor NO_2 concentrations in a randomized study evaluating the efficacy of different interventions to reduce NO_2 concentrations in homes with unvented gas stoves [115]; however, the exact reasons for the lack of efficacy were not clear, as occupant activities were not tracked. A better understanding of the use of kitchen range hoods, as well as their in-situ performance in real buildings, is needed to enhance our understanding of cooking emissions in residential settings and the impact that fuel choice can have on emissions and exposures.

Overall, building electrification is expected to reduce occupant exposure to gas-phase pollutants emitted directly from the combustion processes. When considering a single type of cooking activity, replacing gas stoves with efficient electric stoves is also likely to reduce a portion of UFP emissions. However, due to the substantial magnitude and variability in cooking emissions related to cooking methods and occupant behaviors, the difference in average or peak $PM_{2.5}$ or UFP exposures between homes with and without gas cooking appliances may be relatively small. Increasing the use of appropriately sized and functioning range hoods could be a more effective approach to achieve a significant reduction in cooking emissions and occupant exposure.

2.7. Question 7: What are the health impacts of building electrification?

As people in North America spend more than 90 % of their time indoors, and approximately 70 % of that time in their homes, exposure to indoor pollutants has been linked to significant risks of acute or chronic health effects such as decreased lung function, asthma exacerbation, respiratory irritation and infection, shortness of breath, premature mortality, cardiovascular disease, cancer, and neurological disorders [147–153]. A substantial proportion of indoor pollutants linked to health effects typically comes from fossil fuel combustion in buildings. In a seminal study of the chronic health impacts of residential indoor air pollutants, Logue et al. estimated that NO_2, which is generated indoors primarily from combustion sources, is one of the top ten contributing pollutants to the long-term health burden of indoor air pollution in U.S. residences [154]. Through simulation, Logue et al. [104] further estimated that without the use of a range hood, natural gas cooking burners alone could contribute to 20–30 % of indoor NO_2 and CO concentrations, resulting in 62 % of homes exceeding the acute NO_2 NAAQS (100 ppb) and 9 % of homes exceeding the acute CO California Ambient Air Quality Standard (CAAQS) of 20 ppm. Thus, health benefits are to be expected from the impacts of building electrification on both indoor and outdoor air quality when compared to natural gas appliances and equipment.

The potential health benefits of building electrification are also empirically supported by a limited number of epidemiological studies on gas appliances and health. Most notably, Gruenwald et al. [8] estimated that 12.7 % (95 % CI: 6.3–19.3 %) of current childhood asthma in the U.S. is attributable to residential gas stoves, varying in magnitude by state [8]. These estimates accounted for the proportion of children with gas stoves in their residences as well as a prior meta-analysis of the associations between current asthma and household use of gas for cooking [155], which some suggest does not meet the threshold for causality [156]. However, it is not well understood which pollutant exposures these health impacts are attributed to. For example, in the 2013 meta-analysis, indoor NO_2 was positively, but not significantly, associated with current asthma (OR = 1.09 per 15 ppb; 95 % CI 0.91–1.31) and was significantly associated with current wheeze (OR = 1.15 per 15 ppb; 95 % CI 1.06–1.25), suggesting that NO_2 alone cannot account for the health burden associated with gas cooking. The role that other pollutants, or other factors such as range hood usage and efficacy, might play in any health impacts of building electrification remains poorly understood and largely unaccounted for to date. We are also not aware of any explicit studies of the health impacts of building electrification to date.

Additional health benefits of electrification may also come from improved outdoor air quality. For example, Zhu et al. [128] estimated that replacing all residential heating and cooking gas appliances with electric appliances powered by clean energy would result in annual benefits of \$3.5 billion from reduced mortality and morbidity due to reductions in ambient $PM_{2.5}$ concentrations in California [128]. Fournier et al. [157] similarly estimated that electrification of residential gas appliances in California would create significant net public health benefits in terms of avoided impacts from reductions in ambient $PM_{2.5}$ concentrations [157]. These projections relied on assumptions about future electric grid emissions, such as 100 % zero-emission electricity sources by 2045 in Fournier et al., which may be reasonable for some locations like California but likely not everywhere. To our knowledge, the outdoor air quality and health impacts of widespread electrification have not been projected for other locations or scenarios that do not meet such targets. Furthermore, it is important to note that both gas and electric appliances can have negative health consequences given the risk of severe events such as fires from natural gas leaks or electrical failures, the latter of which could be exacerbated if on-site battery storage is also used. A recent report from the National Fire Protection Association (NFPA) highlighted that households with electric ranges faced an approximately 2.4 times higher risk of cooking fires, 1.9 times higher civilian death rate, 3.6 times higher civilian fire injury rate, and 3.2 times higher associated monetary losses from such fires compared to those with gas ranges [158].

2.8. *Question 8: What are the economic costs of building electrification?*

The economic costs of building electrification range from the costs experienced by the end user to the costs of upgrading the electric grid (see Question 4). The economic costs for end users include the purchasing and installation of new appliances and equipment, upgrading their building's electrical infrastructure, operational electricity use over the new equipment's life cycle, and in most cases the upgrade to the building envelope for older existing buildings. There also non-monetary costs for end users including the time and effort spent researching appliances, applying for rebate programs, and tracking down suppliers and contractors, particularly when the market is not sufficiently developed. Such non-monetized costs are often not considered in cost-benefit analyses, but they can substantially influence occupants' preferences and decisions related to building electrification.

Less et al. [159] reported that the median upfront equipment and installation costs of typical and high-performance residential heat pumps in the U.S. in 2019 were, respectively, \$8,000 and \$12,000, which were at least \$3,000 and \$7,000 higher than a typical gas furnace. However, when a heat pump is used to replace both the furnace and central air conditioner, having a median cost of \$6,000, the price difference becomes negligible. Thus, both the timing and selection of replacement equipment affect the economic costs of heat pump installation. The study also highlights that in order to achieve more than 50 % energy and CO_2 savings, solar PV and typical building energy efficiency measures are needed in addition to the electrification of appliances [159]. These combined strategies have an estimated median CO_2 reduction of 68 %, but come with a median cost of \$54,000, which must be reduced by approximately \$20,000 to break even financially. Building on this approach, a 2022 study of electrification of single-family homes and individually metered multi-family apartments with forced-air heating systems in a local gas utility's service territory in Chicago, Illinois accounted for the capital costs for appliances and impacts on energy bills using both current and expected future retail energy prices [160]. The study focused primarily on electrification of space heating of an average home of each type and projected 20-year net present values (NPV) under several scenarios. The results showed positive NPVs (i.e., economic savings) for end users even without federal incentives (and even greater savings with IRA incentives), and that full electrification (i.e., converting all end uses from gas to electric) actually increased savings compared to partial electrification because it allows end users to eliminate all fixed monthly charges for gas. The magnitude of results was sensitive to factors such as accounting for electrical panel upgrades, projections of future residential natural gas rates, time of replacement, and discount rates, but the NPV estimates always resulted in some degree of savings.

In some cases, costs are not easily reduced through building electrification. A 2021 study conducted in Wales, UK, estimated the GHG abatement costs associated with transitioning to low-carbon technologies for residential space and water heating by comparing conventional heating methods, including gas and electric heaters, to solar PV, biomass boilers, and heat pumps [161]. They found that solar PV offered the most cost-effective GHG savings per unit. In contrast, replacing the existing heating systems with heat pumps would be uneconomical due to the high installation costs and low cost of natural gas in the region. Both the aforementioned studies by Less et al. [159] and Rafique and Williams [161] suggest that policy interventions and incentives are needed to make building electrification financially attractive for households to transition to cleaner and more energy-efficient technologies [159,161].

We also note that, compared to existing buildings, electrification in new building construction has proven to be more financially attractive. The aforementioned 2022 RMI study on residential new construction found that fully electrified homes have both lower upfront and operational costs when compared to new mixed-fuel homes [81]. Additionally, the RMI study showed even greater savings in annual operating costs compared to similar research from 2020 due to the rising gas prices [81,162], although it should be noted that gas prices were impacted by geopolitical events affecting the global gas supply during the time of the study. It further emphasized that the IRA's building provisions could accelerate the shift to all-electric homes by further reducing their costs, especially for low- and moderate-income families.

It is also crucial to recognize that, as customers transition from natural gas utilities due to building electrification, they will stop paying for the operation and maintenance costs of the pipeline infrastructure, shifting their share of energy bill expenses to customers who have yet to make the change. Drawing from empirical data on shrinking utilities, Davis and Hausman [163] predicted that electrification levels of residential buildings of 15 % by 2030 and 40 % by 2040 would translate to an annual increase in natural gas bills by, respectively, \$31 and \$116 per customer [163]. These higher bills could prompt additional customer exit, exacerbating inequality in energy expenditures. Such disparities would particularly impact low-income households and those who are already burdened with higher energy costs.

2.9. *Question 9: What factors influence occupants' preferences related to building electrification?*

Preferences related to building electrification are shaped by several factors, particularly income level [164] and level of knowledge [165–169]. Without sufficient understanding of the technical aspects of energy production, people are less likely to make "one-shot" purchases of energy-efficient appliances, which offers much less support for an elaborate transition to renewable energy [167,170]. Also important in affecting choices related to electrification is political ideology focusing on the energy transition [171,172], the extent to which a person discounts future events [173], and the high costs of electrification [166, 174–176]. Under residential conditions, renters may use more electric appliances than owners [177], but some building owners may disproportionately shift the costs of building electrification to their tenants [178,179]. Electrification is thus partly a function of residential and commercial buildings-related market conditions, and it could very well lead to rental premiums that have been identified in analogous initiatives, e.g., LEED certification [180].

Preferences for building electrification have recently been assessed within the context of people's decisions regarding heating. For example, a 2021 study on heating electrification-related choices made by millions of U.S. households over a 70-year period identified five key factors – energy price, geography, housing type, climate, and household income –

that collectively account for over 90 % of the increase in electrification for heating since 1950 [181]. Most significant among these factors are changes in energy prices for oil, natural gas, and electricity, which together explain more than 70 % of the observed increase in heating electrification. Geography and climate also play an important role, as households in colder states (e.g., Pennsylvania, New York, Vermont, and Montana) are willing to pay more than $1,000 annually to avoid electrification [182]. This is echoed in a recent survey of residences in the U. S. (n = 10,000) that identified statistically significant regional differences in terms of people's willingness to adopt energy efficiency-related technologies [183]. For instance, respondents from the U.S. West are more eager to adopt decarbonization technologies such as heat pumps for space and water heating when compared to respondents from the U. S. Midwest. Those living in the West are also more motivated to reduce their environmental impacts when compared to people living in the Midwest, Northeast, and Southeast. Interestingly, people in the West also had a higher adoption rate for gas stoves, indicating that cooking-related decisions may be distinct from decisions for heating and other technologies.

The success of heating electrification is also impacted by people's concerns about decarbonization technologies. On the subject of refrigerant leakage from heat pumps, for instance, the National Resources Defense Council (NRDC) published a blog post in 2022 entitled "Don't let refrigerants slow heating decarbonization," which summarized the aforementioned Pistochini et al. study to address the uncertainties around refrigerant leakage [184]; i.e., the net GHG impacts of heating electrification, including refrigerant leakage, present a substantive perceived barrier to the implementation of heat pump programs. Research has also shown that there are widespread concerns among the public about the performance of heat pumps in extreme weather, the reliability of the electricity grid, challenges in the rebate submission process, the high initial costs and long payback periods, the shortage of reliable contractors, lack of familiarity with new technologies, and disruptions associated with major retrofits [1,185–187]. For these reasons, increased knowledge and rebate programs by themselves are unlikely to affect widespread residential retrofitting [188].

People's preferences about building electrification also partially reflect their decisions regarding cooking, including whether they have gas or induction stoves, among many other factors. Nationally, approximately 53 % of homes in the U.S. have electric stoves while 28 % have gas stoves as their primary cooking range, but the proportion of electric or gas stoves varies regionally. For example, the ratio of electric-to-gas stoves is approximately 0.7 in mixed-and-hot-dry climate regions, 1.7 in cold/very-cold climate regions, and 5.0 in hot-humid climate regions [189]. Interviews with industry experts, homeowners, and renters indicate that cultural factors, cooking preferences, and familiarity with gas stoves create a barrier to transitioning to electric induction stoves [175,190–193]. Given the interactive and central role that stoves play in the home, the considerations involved when replacing stoves are substantially different from appliances that only provide heat. For instance, in 2023, the U.S. Consumer Product Safety Commission (CPSC) released a Request for Information (RFI) on the health hazards of gas stoves and possible solutions, preceded by a public statement by the CPSC commissioner about the possibility of banning gas stoves [194]. Having received more than 9,000 comments on the RFI, the backlash "set off a political firestorm" against such a ban [195]. This reflects a similar occurrence in 2019 that followed announcements about the California Energy Commission's Building Decarbonization BUILD and TECH programs [196]. Public antipathy toward the gas-limited measures proposed in the BUILD and TECH programs resulted in the California Public Utilities Commission's fact sheet, which clarified that gas could still be used in buildings, that homes did not need to be retrofitted, and that energy bills would not skyrocket. Similar to heating, people's cooking-related preferences and willingness to shift from gas to electric stoves are likely to vary across regions given differences in usage [183].

Clearly, people hold strong opinions about fuel options and energy costs in their homes, and the relationship between preferences and energy use is complicated. This could be the result of a "double invisibility problem" – that energy cannot be seen nor easily connected to one's everyday activities [197], but it could also be the result of how people utilize information in unexpected ways. For instance, when people were informed on their bills that their energy use was significantly less than that of their neighbors, it was found that they increased their household energy use [198]. In another instance, more politically conservative individuals supported energy conservation efforts, but only when it was framed as a "tax rebate" rather than a "tax subsidy" [199]. Perceived challenges about the energy transition process, particularly the availability of the repair and replacement parts, are concerns for people [183, 190]. Yet, people positively view the prospect of home electrification when considering the air quality and climate change-related improvements [200]. To modify people's beliefs around such building energy transitions, government-originating communications can highlight the benefits of the energy transition while acknowledging such heterogeneous household characteristics [201,202].

2.10. Question 10: What is needed to understand and optimize the impacts of an equitable transition to building electrification?

Our review of the literature suggests there are several categories of needs to understand and optimize the impacts of widespread building electrification in an effective and equitable manner, ranging from technical to economic to social to political. Underlying these needs is the understanding that prior energy transitions in the U.S., such as recent transitions from coal to natural gas and biomass, have led to inequities in impacts on air quality and health, with excess burdens placed on underserved communities [203,204]. We know that low-income households spend a greater share of their income on core needs such as housing, transportation, and food, which includes energy costs as a substantial contribution [205]. Across the U.S., low-income citizens are more likely to be uncomfortably cold in their homes, and race is associated with heating inadequacy [206]. In Illinois specifically, low-income families spend an average of 13 % of their income on household energy [207]. In Chicago, Black, Hispanic, older adults, renters, and low-income multi-family building residents all have disproportionately higher energy burdens than the median household [208]. At present, we can choose to pursue decarbonization pathways that ignore the existing fragile infrastructure of these underserved communities and their older existing buildings and systems, or we can engage local communities to be a part of the solution by improving their existing infrastructure and adopting decarbonization pathways tailored to overcome these constraints. Consequently, a practical and equitable building decarbonization plan must account for the short-term and long-term impacts of deep decarbonization technologies on both primary factors that directly influence people (i.e., via energy, economic, air quality, and health burdens) as well as secondary factors that account for their side effects on the environment (i.e., via the impacts of refrigerants, embodied energy, and GHG emissions from manufacture and operation on climate change) in underserved communities. Because of the differences in natural gas and electricity prices, federal policy measures such as subsidies are also needed to ensure that lower-income households can electrify without increasing their operational costs, in addition to the upfront installation costs.

Moreover, there is increasing evidence of racial disparities in access to the benefits of low-carbon technologies. For example, only 8 % of the U.S. energy efficiency workforce is Black or African American compared to the national average of 12 % [209,210]. Racial and ethnic inequities also exist in the share of the burden of externalities resulting from energy consumption and production that are faced by the population. Black and Hispanic minorities bear a disproportionate burden from the air pollution caused mainly by non-Hispanic whites, on average, with an excess "pollution burden" of approximately 60 % compared to white populations [211]. We also know African Americans are particularly vulnerable to the effects of climate change based on geography, underlying health disparities, energy access, and employment [212]. As we have stated already, building decarbonization pathways should also include widespread adoption of energy efficiency measures and increased renewables (e.g., PV panels). However, we already know in the U.S. Black and Hispanic-majority communities have installed less PV than white-majority communities; 69 % and 30 % less, respectively, accounting for differences in household income and home ownership [213]. The majority of these underserved communities have a slightly lower potential for PV, but this does not justify the inequities in PV adoption. An equitable approach to decarbonization is feasible only when the communities are engaged and there are policies, programs, and incentives that center on racial equity [214]. Therefore, community engagement is critical for equitable decarbonization.

Overall, we recommend the following research needs to better understand and optimize the impacts of an equitable transition to building electrification.

- Assessment of the impacts of building electrification on indoor air quality and health at scale and across diverse populations
- Measurement of the in-situ performance characteristics of electrified buildings, both new and retrofit, to demonstrate performance and answer common questions that may otherwise be barriers to adoption
- Exploration of what influences people's decisions and actual adoption of building electrification and how they vary by geographical, climate, and socioeconomic factors
- Understanding of the broader implications of electrification on the grid across all sectors (e.g., buildings, industrial, and transportation)
- Life cycle evaluation of local, regional, and national approaches to electrification across technical, social, behavioral, economic, and political dimensions

3. Conclusion

From a technical perspective, it is clear that comprehensive life cycle assessments are needed to fully account for and understand the impacts of building electrification on energy use, climate change, indoor and outdoor air quality, and human health in the short, medium, and long term. An immediate need for future research on the technical aspects of building electrification is to quantify these net impacts in different geographic locations, and to integrate those technical assessments with social-behavioral research on the effectiveness of different strategies and policies in promoting building electrification. Yet, we must employ social-behavioral research to understand how these factors and impacts differ across communities with different demographics and socioeconomic statuses such that an equitable distribution of the benefits of building electrification can be attained for all communities. Finally, to close the loop, research is needed to understand the actual impacts and effectiveness of policy actions and incentives that promote building electrification.

CRediT authorship contribution statement

Tianyuan Li: Writing – review & editing, Writing – original draft, Formal analysis, Conceptualization. **Matthew A. Shapiro:** Writing – review & editing, Writing – original draft, Formal analysis. **Mohammad Heidarinejad:** Writing – review & editing, Writing – original draft, Formal analysis, Conceptualization. **Brent Stephens:** Writing – review & editing, Writing – original draft, Formal analysis, Conceptualization.

Declaration of competing interest

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No data was used for the research described in the article.

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