In the Air Tonight: How Residential Electrification Can Lead to Cleaner Air and Better Health

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ABSTRACT

The detrimental health effects of burning fossil fuels are well documented. The combustion of fossil fuels to heat our homes, cook our food, dry our clothes, and heat our water contributes not only to a warming climate but also to premature mortality, heart attacks, asthma, and other morbidities. Continued use of these fuels disproportionately harms communities of color who simultaneously experience higher than average levels of pollution exposure and who experience systemic and financial barriers to upgrading their homes to efficient electric appliances. At the same time, there is a lack of granular, community-level data on the health impacts and associated costs of burning fossil fluels in the residential sector. A limited awareness of the positive health effects of electrification for specific communities limits the potential for community-led advocacy.

We used open-source, large-scale building energy modeling data from the National Renewable Energy Laboratory's (NREL) ResStock tool to estimate the criteria air pollutant (CAP) emissions impacts of home electrification upgrades for all households in the contiguous US. We then modeled the concentration of fine particulate matter – the driver of a range of negative health effects – at a high spatial granularity using an open-source pollution transport model. We quantified the health impacts of these pollutant concentrations, both in terms of higher incidence of premature mortality and the economic cost. The outcome is a tool which allows communities to highlight local health benefits when advocating for residential electrification.

Introduction

Combustion of fossil fuels in the home for a variety of end uses, such as space and water heating, emits carbon monoxide, nitrogen dioxide, fine particulate matter, benzene, and other pollutants known to be hazardous to human health (California Air Resources Board, n.d; Lebel 2022). These pollutants contribute to poor indoor and outdoor air quality and adverse health impacts, including an elevated risk of childhood asthma for households with gas stoves (Gruenwald et al. 2023). Continued use of these fuels disproportionately harms people of color, who face systemic barriers in accessing efficient electric appliances and are exposed to higher pollution burdens (Tessum et al. 2021).

While much research has been done on the nexus of *indoor* air quality and health consequences of residential fossil fuel combustion, comparatively little research has quantified the contribution of residential fossil fuel combustion to poor *outdoor* air quality, cumulative pollution burden, and the associated health impacts and costs. This knowledge gap regarding outdoor air pollution leads to a limited awareness of the air quality and environmental justice benefits of electrification and a lack of health-related data for community advocates. This analysis calculates the health impacts and associated costs of poor ambient air quality resulting from residential fossil fuel combustion and the avoided health impacts due to electrification at the household and community level.

Previous analyses that applied a similar framework include a 2021 paper quantifying the outdoor air quality and health benefits of the transition away from coal in the U.S. from 2008 to 2017 (Buonocore et al. 2021). Previous work by the Rocky Mountain Institute analyzed $PM_{2.5}$ pollution from residential fossil fuel combustion at the 10-km grid scale and how these pollution burdens overlap with existing areas with $PM_{2.5}$ levels over current pollution limits, and demonstrated that pollution exposure from residential fossil fuel combustion disproportionately impacts communities of color (Dennison et al. 2021). This analysis expands on this work by quantifying the avoided health impacts and costs attributable to specific residential building electrification measures.

This analysis will help advocates and policy makers gain an understanding of the degree to which residential fossil fuel combustion contributes to air pollution and associated negative health impacts at the community scale, and to what extent electrification can mitigate these air quality and health impacts.

Materials and Methods

Scope

To quantify the health impacts of residential fossil fuel combustion and the potential benefits of residential building electrification, this study estimates the health impacts associated with a change in exposure to ambient concentrations of fine particulate matter that may result from an electrification retrofit — defined as the replacement of a fossil fuel-powered residential appliance with one powered by electricity. We consider the replacement of inefficient electric appliances with more efficient versions to be electrification retrofits as well, as in the case of installing an air source heat pump to replace electric resistance heating.

Ambient concentrations of fine particulates, defined as particulate matter less than 2.5 microns in diameter ($PM_{2.5}$), are a consequence of direct $PM_{2.5}$ emissions (primary $PM_{2.5}$) and the formation of $PM_{2.5}$ through chemical reactions in the atmosphere involving other pollutants (secondary $PM_{2.5}$). Primary $PM_{2.5}$ is a byproduct of fossil fuel combustion in residential appliances and fossil fuel-powered electricity generation. Secondary $PM_{2.5}$ results from chemical reactions involving emissions of volatile organic compounds (VOC), ammonia (NH_3), nitrogen oxides (NO_x), and sulfur oxides (SO_x), which themselves are also byproducts of fossil fuel combustion in residential appliances and fossil fuel-powered electricity generation. Together, these pollutants are considered criteria air pollutants (CAP) by the Environmental Protection Agency (EPA) and are subject to stringent regulations limiting their emissions due to their adverse effects on public health (EPA 2024). This study evaluates the community-scale health impacts of decreases in ambient $PM_{2.5}$ concentrations resulting from residential building electrification.

This section proceeds with an explanation of the methodology used to estimate CAP emissions and health impacts and costs from residential fossil fuel combustion and electricity generation. We then explain how we integrate these impacts with building energy modeling to produce community-level estimates for avoided premature mortality associated with different electrification retrofits. This analysis excludes the effects of ground-level ozone on health, which forms when NO_x and VOCs interact with ultraviolet light from the sun. Additionally, while there is extensive research documenting the effects of fossil fuel combustion on indoor air quality and health (ALA 2022), this study is constrained to outdoor air quality.

Estimating the emissions and increases in premature mortality from fossil fuel combustion in residential buildings

To estimate exposure and thus adverse health effects of ambient $PM_{2.5}$ concentrations associated with residential fossil fuel combustion, we first estimated CAP emissions at a high spatial granularity using a combination of American Community Survey (ACS) data published by the U.S. Census Bureau, National Emissions Inventory data (NEI) published by the EPA, and state-level energy consumption estimates for the residential sector published by the Energy Information Administration (EIA). Then, using these CAP emissions quantities, we modeled ambient concentrations of $PM_{2.5}$ in the atmosphere using an open-source pollution transport model called Intervention Model for Air Pollution (InMAP) . Finally, we calculated the increases in premature mortality and associated costs of $PM_{2.5}$ concentrations associated with residential fossil fuel combustion.

The NEI data is published at the county level. Given the size and population of some large counties, this spatial granularity is insufficient to capture variations in exposure to ambient $PM_{2.5}$ concentrations associated with residential fossil fuel combustion. As such, we devised a methodology to downscale the published, county-level NEI data from 2020 to the census tract-level using data from the 2020 ACS on household primary heating fuel and EIA data on fossil energy consumption in the residential sector from 2020.

To estimate county-level CAP emissions quantities, the NEI takes state-level energy consumption data for a given fossil fuel in the residential sector from the EIA and allocates it to counties based on the county-level household count using that fuel as their primary heating fuel. More specifically, they take the ratio of county-level to state-level household counts for a given fuel type and apply it to the state-level energy consumption estimate for that fuel type by the residential sector. They then apply an emissions factor specific to each CAP and fuel type to this ratio to estimate total CAP emissions quantities for each fuel at the county-level (EPA 2020). To downscale these CAP emissions quantities to the census tract level, we substitute the county-level household counts with tract-level household counts that use each fuel as their heating fuel to calculate tract-level fuel consumption, and then apply fuel-specific CAP emissions factors to tract-level fuel consumption. The tract-to-state ratio is thus calculated as follows:

$$R_{f,t,s} = \frac{HU_{f,t}}{HU_{f,s}}$$

Where:

$R_{f,t,s}$ = ratio of homes in tract *t* to homes in state *s* using fuel *f* as primary heating fuel

$HU_{f,t}$ = housing units in tract *t* using fuel type *f* as primary heating fuel

$HU_{f,s}$ = housing units in state *s* using fuel type *f* as primary heating fuel

The tract-level fuel consumption is then calculated as follows:

$$FC_{f,t} = FC_{f,s} \times R_{f,t,s}$$

Where:

$FC_{f,t}$ = fuel consumption of fuel type *f* in tract *t*

$FC_{f,s}$ = fuel consumption of fuel type *f* in state *s*

$R_{f,t,s}$ = ratio of homes in tract *t* to homes in state *s* that use fuel type *f* as primary heating fuel

These equations are appropriate for all fuels except fuel oil. For fuel oil, the EIA distinguishes between kerosene and distillate fuel oil, while the ACS does not. As such, to calculate how many housing units in a state use kerosene vs distillate fuel oil, we first calculated the ratio of kerosene and distillate fuel oil consumption to total kerosene and distillate fuel oil consumption in a given state. We then applied this ratio to the ACS count of households at the state- and tract-level using any fuel oil as their primary heating fuel. This is indicated in the following two equations:

$$R_{dfo/ker,s} = \frac{FC_{dfo/ker,s}}{FC_{dfo,s} + FC_{ker,s}}$$

Where:

$R_{dfo/ker,s}$ = ratio of residential distillate fuel oil *or* kerosene to total distillate fuel oil and kerosene in state *s*

$FC_{dfo/ker,s}$ = Fuel consumption of distillate fuel oil OR kerosene in state *s*

$FC_{dfo,s}$ = Fuel consumption of distillate fuel oil in state *s*

$FC_{ker,s}$ = Fuel consumption of kerosene in state *s*

$$HU_{dfo/ker,t} = HU_{fo,t} \times R_{dfo/ker,s}$$

Where:

$HU_{dfo/ker,t}$ = housing units in tract *t* using distillate fuel oil OR kerosene as primary heating fuel

$HU_{fo,t}$ = housing units in tract *t* using any fuel oil as primary heating fuel

$R_{dfo/ker,s}$ = ratio of residential distillate fuel oil or kerosene to total distillate fuel oil and kerosene in state *s*

To calculate the CAP emissions factors specific to each fuel type, we divided the NEI-reported total CAP emissions quantities from the residential sector and for each fuel type at the state-level by the EIA-reported state-level energy consumption of each fuel type by the residential sector. We then converted all emissions factors to tons per kilowatt hour, and applied these emissions factors to the tract-level fuel consumption for each fuel type to estimate tract-level CAP emissions quantities. This process is described in the following equations:

$$EF_{p,f,s} = \frac{CAP_{p,f,s}}{FC_{f,s}}$$

Where:

$EF_{p,f,s}$ = Emissions factor for pollutant *p* associated with fuel type *f* in state *s*

$CAP_{p,f,s}$ = CAP emissions quantity for pollutant *p* associated with fuel type *f* in state *s*

$FC_{f,s}$ = Fuel consumption of fuel type *f* in state *s*

$$CAP_{p,f,t} = EF_{p,f,s} \times FC_{f,t}$$

Where:

$CAP_{p,f,t}$ = CAP emissions quantity for pollutant *p* associated with fuel type *f* in tract *t*

After calculating the CAP emissions quantities associated with residential fossil fuel combustion at the census tract-level, we then modeled the transport, formation, and concentration of $PM_{2.5}$ associated with each CAP using the open-source pollution transport model Intervention Model for Air Pollution (InMAP).

InMAP is a reduced complexity model (RCM) that models the formation and concentration of $PM_{2.5}$ from its precursors in the ambient air given spatially defined emission quantities. It is considered an RCM because it aims to approximate the results of a full chemical transport model such as the Community Multiscale Air Quality Model (CMAQ) or the Comprehensive Air Quality Model with Extensions (CAMx) without incurring the same level of computational expense (full chemical transport models may require a supercomputer). Extensive literature has documented the performance of InMAP relative to full chemical transport models, with results indicating that the outputs of InMAP are within published air quality model performance criteria (Tessum, Hill, and Marshall 2017; Thakrar et al. 2022; Baker et al. 2020).

InMAP takes as inputs the tract-level CAP emissions quantities described above, population data, baseline mortality incidence data, and a set of default meteorological, pollutant, and geospatial data. Using the ACS application programming interface, we pulled 2020 census tract-level population data for use as an input into InMAP. We used 2020 county-level mortality incidence data in deaths per 100,000 people from the CDC's WONDER database (CDC 2020).

InMAP outputs geospatial data indicating the daily average ambient concentration of $PM_{2.5}$ at varying grid cell sizes across the contiguous US resulting from the transport and atmospheric chemical reactions of the CAP emissions quantities used as inputs. The grid cell sizes vary according to the population density. As such, the InMAP outputs will be more spatially granular in high population density areas like cities. The data are presented in $\mu g/m^3$ (micrograms per cubic meter).

Using the InMAP outputs of $PM_{2.5}$ concentrations in the ambient air, we then calculated the increase in premature mortality incidence and the associated cost associated with exposure to fine particulates.

We used two effect sizes drawn from two widely cited papers estimating the statistical relationship between $PM_{2.5}$ exposure and premature mortality (Krewski et al. 2009; Lepeule et al. 2012). Together, the effect sizes drawn from these papers constitute low and high estimates, respectively, in EPA analyses (EPA 2023). For our final estimate of premature mortality, to present a single number, we took the mean of these low and high estimates. To assign an economic valuation to the incidence of premature mortality, we multiplied the premature mortality estimate by a value of statistical life (VSL) figure of $11.5 million in 2024 dollars, following the EPA's recommendation of a $7.4 million VSL in 2006, updated for inflation, using the Consumer Price Index (EPA 2024b).

Estimating the emissions and increases in premature mortality from electricity generation

The adverse health impacts from electricity demand are caused by fossil fuel combustion in electricity generation and the associated production of CAPs and their contribution to ambient concentrations of $PM_{2.5}$. Residential electrification can impact the demand for electricity at a household level in two ways. First, shifting residential end uses from fossil fuel burning appliances like a methane-gas furnace to an electrical appliance like an air-source heat pump can increase the total electricity demand for a household. Second, households which upgrade their legacy electric resistance appliances to more efficient induction or heat pump technologies will see a net decrease in electricity demand for that end use.

To estimate the premature mortality impacts from changes in residential electricity consumption, we employed a similar process as residential fossil fuel combustion. First, we calculated forward-looking CAP emissions factors for electricity generation using CAP emissions quantities reported by the 2020 NEI, annual electricity generation figures reported by the EIA, and NREL's electric grid forecasting model Cambium. We then modeled ambient $PM_{2.5}$ concentrations associated with CAP emissions from electricity generation using the NEI data, InMAP, and the same set of additional inputs as were used in estimating concentrations associated with residential fossil fuel combustion. We then used these ambient $PM_{2.5}$ concentrations associated with electricity generation as inputs to calculate changes in premature mortality incidence.

The NEI reports CAP emissions quantities associated with different fuel types from electricity generating locations throughout the US. We summarized these at the state-, fuel source-, and pollutant- level. We divided these totals by the total annual electricity generation figures published by the EIA. The annual electricity generation data is available by state and fuel type. The baseline emissions factor is then calculated as

$$EF_{e,p,f,s} = \frac{CAP_{e,p,f,s}}{EG_{f,s}}$$

Where:

$EF_{e,p,f,s}$ = Emissions factor for electricity generation *e* for pollutant *p* from fuel *f* in state *s*

$CAP_{e,p,f,s}$ = CAP emissions quantity from electricity generation *e* for pollutant *p* associated with electricity generation using fuel type *f* in state *s*

$EG_{f,s}$ = Electricity generation (in tons) from fuel type *f* in state *s*

The baseline emissions factors represent the tons of pollutants associated with each kWh of generation in the present day. However, to adequately capture the impact that a decarbonizing electricity sector will have on CAP emissions, we used grid forecast scenarios from Cambium. We chose the 2022 grid forecast associated with a 95 percent carbon-free grid by 2050, which models an increase in solar and wind electricity production and an associated fall in both greenhouse gasses and CAPs. Cambium publishes the estimated generation by energy source per state through the year 2050. We used this generation forecast to calculate how the emissions factor for each state would change through 2038 (representing the approximate life span of a heat pump which is installed in 2023). We calculated the adjusted emissions factor by weighting each fuel's emissions factor by the forecasted generation from that fuel in each year, to arrive at an emissions factor which combines different fuels into an aggregate. We did not use a discount rate in the current modeling. The adjusted present-day emissions factor is then represented as:

$$EF_{p,s}^{adj} = \frac{\sum_{i=2023}^{2038}\left(EF_{p,f,s} \times EG_{f,s,i}\right)}{\sum_{i=2023}^{2038} EG_{s,i}}$$

Where:

$EF_{p,s}^{adj}$ = adjusted emissions factor for pollutant *p* associated with electricity generation in state *s*
$EF_{p,f,s,}$ = present-day emissions factor for pollutant *p* associated with electricity generation from fuel *f* in state *s*
$EG_{f,s,i}$ = electricity generation (in MWh) from fuel *f* in state *s* in year *i* from Cambium
$EG_{s,i}$ = electricity generation (in MWh) in state *s* in year *i* from Cambium

This equation enabled us to calculate emissions factors for each state. However, since import and export of electricity between states is commonly used to meet electricity demand, we translated our state level emissions factors to EPA's eGRID subregions, which were developed to minimize the import and export of electricity outside their boundaries to reflect the fact that electricity demand in one state may not be fully met by generation within that state (EPA 2024b). We then calculated emissions factors for each subregion using the following equation:

$$EF_{p,reg} = \frac{\sum_{c \in reg}(EF_{p,c} \times EG_c)}{\sum_{c \in reg} EG_c}$$

Where:
$EF_{p,c}$ = the emissions factor for pollutant *p* and county *c,* where the state-level emissions factors are assigned to all counties within them
EG_c = the total electricity generation for the county *c*
$EF_{p,reg}$ = the emissions factor for pollutant *p* in region *reg*
$c \in reg$ = the counties located within each subregion

As mentioned previously, to calculate the health impacts of electricity generation, we followed a similar process as residential fossil fuel combustion. We used point-source CAP emissions quantities associated with electricity generation from the NEI in InMAP, supplementing them with stack height, velocity, and diameter parameters from the EPA. The stack height parameters enable the model to account for the fact that pollutants from electricity generating stations are generally emitted well above ground level, increasing the total distance they can travel (EPA 2018). We processed the pollutant concentrations from InMAP using the Krewski and Lepeule health impact functions and the baseline all-cause mortality in each grid cell. We then mapped the resulting premature mortality incidence totals and costs output from the InMAP grid to the eGRID subregions and summed them within each region to estimate total health impacts and costs associated with electricity generation in each subregion.

Integrating total health impacts and costs with building energy modeling

Understanding the total health impacts and associated costs caused by residential fossil fuel combustion and electricity generation does not in itself allow us to estimate the avoided health impacts and costs of residential building electrification. To do that, we need estimates for the changes in fossil fuel and electricity consumption resulting from a given electrification retrofit and a methodology to quantify how that change results in health impacts and associated costs. We used data from NREL's ResStock End Use Savings Shapes 2022.1 Release to provide estimates of changes in fossil fuel and electricity consumption resulting from a given electrification retrofit, and we devised health impact factors we can apply to these changes in fossil fuel and electricity consumption to quantify health impacts and costs of electrification retrofits.

The ResStock End Use Savings Shape dataset is a set of approximately 550,000 building energy simulations output by EnergyPlus, a building energy simulation program developed by the Department of Energy (DOE) (NREL 2024). ResStock's building energy simulations are meant to statistically represent the US residential housing stock, conforming to known distributions of various housing characteristics such as square footage, primary heating fuel, housing typology, and many others. Each building energy simulation model represents approximately 242 households in the real world, and also pertains to a specific state, county, and Public Use Microdata Area (PUMA)[1]. In addition to modeling the baseline energy consumption of the US housing stock, NREL used EnergyPlus to model the energy consumption of the US housing stock under several electrification and efficiency retrofit scenarios such as installation of air source heat pumps, heat pump water heaters, and induction stoves. We supplemented these scenarios with our own modeled scenarios. The full list of upgrades we're considering in this analysis are described below in table 2. Rewiring America modeled scenarios below were modeled using our own building energy modeling on the same 550,000 building energy models used in ResStock, with different heat pump specifications as described below. The rooftop solar modeling

Table 2 - Modeled electrification upgrade scenarios

Upgrade	Details
Heat Pump	Retirement of existing heating/cooling and installation of an air-source heat pump with performance similar to a centrally-ducted, variable speed SEER 18 and 10 HSPF heat pump with electric resistance backup, or a ductless mini-split with SEER 18 and 10.5 HSPF, sized using HERS methodology and without a setpoint setback. Rewiring America modeled scenario.
Insulation and Weatherization	The modeled weatherization package includes attic floor insulation up to IECC-Residential 2021 levels, general air sealing to achieve a 30% reduction in ACH50, duct sealing to 10% leakage, and R-13 drill-and-fill insulation (if the home currently has wood stud walls with no insulation).
Heat Pump and Weatherization and Insulation	Installation of both an air-source heat pump (with performance specs described above) and the weatherization package. Rewiring America modeled scenario.
Rooftop Solar	Installation of rooftop photovoltaic panels, sized based on the potential electricity demand for a fully electrified home and the home's approximate rooftop size. The estimated generation of that solar is compared to the home's current electricity demand to estimate the annual electricity savings. Rewiring America modeled scenario.

[1] Public Use Microdata Areas refer to geographic extents used by the US Census Bureau for collecting survey responses for the ACS. They are coterminous with states.

Heat Pump Water Heater	Retirement of existing water heater and installation of a heat pump water heater.
Heat Pump Dryer	Retirement of existing dryer (if applicable) and installation of a heat pump dryer.

To quantify the avoided health impacts and costs associated with a net reduction in CAP emissions from electrification, we developed health impact factors describing the health benefit *per ton of pollutant emitted* using our estimates of total avoided premature mortality incidence and associated costs (based on the VSL) and total CAP emissions quantities from residential fossil fuel combustion and fossil fuel combustion in electricity generation. These health impact factors are analogous to "benefit per ton" of avoided CAP emissions metrics developed by the EPA (Fann, Baker, and Fulcher 2012). To account for the fact that some emissions emitted by households within a county will drift to adjacent counties, leading to health impacts there, we included a 15-kilometer buffer around each county's boundary when allocating health impacts and emissions to each county. The buffer size was determined by running individual counties through our modeling pipeline and increasing the buffer size to capture a larger percentage of health impacts from that county. We therefore calculated the county-level benefit per ton of avoided CAP emissions from residential fossil fuel combustion as follows:

$$BPT_{h,p,c} = \frac{H_{i/v,p,c}}{CAP_{p,c}}$$

Where:

$H_{i/v,p,c}$ = Total health impact *i* or valuation *v* associated with pollutant *p* in county *c* plus a 15-km buffer

$CAP_{p,c}$ = Total volume, in tons, of pollutant *p* in county *c* plus a 15-km buffer

$BPT_{h,p,c}$ = Benefit per ton of emitted pollutant *p* in county *c* for health impact h

We calculated the eGRID subregion-level benefit per ton of avoided CAP emissions from electricity generation as follows:

$$BPT_{h,p,reg} = \frac{H_{i/v,p,reg}}{CAP_{p,reg}}$$

Where:

$H_{i/v,p,reg}$ = Total health impact *i* or valuation *v* associated with pollutant *p* in subregion *reg*

$CAP_{p,reg}$ = the total volume, in tons, of pollutant *p* in subregion *reg*

$BPT_{h,p,reg}$ = the benefit of health impact *h* per ton of emitted pollutant *p* in subregion *reg*

In order to estimate the health impacts and costs of a specific electrification retrofit, we first estimate the change in CAP emissions associated with the change in fossil fuel and electricity consumption for a particular retrofit. To do this, we applied the CAP emissions factors for residential fossil fuel combustion and electricity generation described above to changes in fossil fuel and electricity consumption between the baseline building energy simulations and the simulations under electrification retrofit scenarios in ResStock. This process is described in the following equation:

$$B_{h,b,r} = \Delta EC_{b \in c,r,f} \times EF_{f,p,c} \times BPT_{h,p,c}$$

Where:
$\Delta EC_{b \in c,r,f}$ = change in energy consumption of fuel *f* for building *b* in county *c* and electrification retrofit *r*
$EF_{f,p,c}$ = emissions factor for fuel *f*, pollutant *p*, and county *c,* where the state-level emissions factors are assigned to all counties within them
$BPT_{h,p,c}$ = benefit per ton of avoided pollutant *p* for health impact *h* in county *c*
$B_{h,b,r}$ = savings (incidence or cost) associated with health impact *h* for building *b* in county *c* and retrofit *r*

With a county-level figure for avoided health impacts and costs under different electrification retrofit scenarios for each building energy simulation in ResStock, we can aggregate these at various geographic levels to present a community-level view of the health savings of a particular electrification retrofit.

Results & Discussion

The avoided health impacts and costs vary across geographies based on the local grid composition, population density, and baseline incidence rates of various health morbidities, but we do see some patterns emerge in the aggregate. The average avoided health costs for different electrification retrofits are presented in Table 3 below. Across the contiguous 48 states and D.C., retrofitting a household with a heat pump while simultaneously adding insulation avoids an average of $259 in annual health costs over the lifetime of the appliance. This cost incorporates the positive health impacts of removing fossil fuel combustion in the home, along with the incremental negative impacts of increased electricity consumption for households switching from primarily fossil-fuel based heating. Rooftop solar also has a high impact - the $269 average annual impact represents the benefits of shifting a household's electricity demand from being met by electricity generation from the grid.

Table 3 - National average annual health and estimated bill savings by electrification upgrade

Upgrade	Average Annual Health Savings	Estimated Average Bill Savings[2]
Heat Pump and Insulation	$259	$650
Heat Pump Water Heater	$68	$159
Heat Pump	$159	$371

[2] Bill savings are calculated by multiplying changes in energy use by fuel-specific utility-average energy prices, sourced from the EIA, NREL's Utility Rate Database, American Gas Association, and the Homeland Infrastructure Foundation-Level (HIFLD) Database.

Heat Pump Dryer	$8	$30
Insulation	$157	$417
Rooftop Solar	$269	$1,047

The annual health savings are of a meaningful scale relative to the bill savings that we already use to communicate the benefits of electrification. While the health savings are felt at the community level and not necessarily individually for each household, they can be attributed to each household through this modeling approach and represent a significant net benefit to the community.

Across the country, households switching from fuel oil-based heating systems have the greatest positive health impacts of a heat pump and insulation, as shown in Table 4 below. The savings also incorporate the positive impacts of decreased electricity demand from upgrading an existing air-conditioning unit to a higher efficiency heat pump, as well as the decreased load from insulating the building. The magnitude of the differences provides useful information for policymakers and advocates considering which households to prioritize for electrification.

Table 4. National average annual health savings after a heat pump and insulation upgrade

Baseline (Pre-Upgrade) Heating Fuel	Average Annual Health Savings
Fuel Oil	$634
Natural Gas	$281
Electricity	$179
Propane	$128

The detailed demographic information available in ResStock also allows us to make more targeted estimates of the avoided health costs of electrification in specific cities and for specific types of households. For instance, we estimated that retrofitting all of the 16,000 households with a heat pump and insulation in the city of Plainfield, New Jersey would yield approximately $150 million in avoided health costs over the 15-year lifetime of the appliances.

By contrast, retrofitting the same number of households in Elmhurst, Illinois would yield about $100 million in avoided health costs over the same time frame. The difference in estimates is explained by a variety of factors, including the difference in population density of the two cities (Plainfield is about twice as dense as Elmhurst), the difference in baseline health incidence rates, the current fuel-mix used for generating electricity in each city's region, and the existing heating fuel distributions. One of the advantages of our approach is the ability to account for these different factors to understand the net health impacts from electrification.

Using the fuel- and geography-specific CAP emissions factors, we can also quantify the avoided CAP emissions quantities associated with each electrification upgrade, shown below in Table 6. Reducing CAP emissions is a primary goal of many government-funded grant programs, so this analysis may be particularly useful to groups seeking to quantify the air quality impacts of their residential electrification programs.

While almost every major upgrade decreases, on average, the net volume of pollutants associated with that home appliance, we do note that the heat pump upgrades lead to a net increase in sulfur-dioxide emissions compared to the baseline heating fuel. Our modeling suggests this is a result of electricity generation emitting the most sulfur dioxide per kilowatt-hour of usage compared to the other heating fuels, primarily because of power plants that burn coal. If the grid decarbonizes faster than expected, these results would change accordingly.

Table 6: Average Annual Avoided Criteria Air Pollutants (kg) for a Heat Pump and Basic Insulation Upgrade

Upgrade Option	NH3	NOx	Primary PM2.5	SO2	VOC
Heat Pump and Insulation	0.379	2.183	0.042	-0.077	0.119
Heat Pump Water Heater	0.073	0.409	0.009	0.029	0.023
Heat Pump	0.373	1.974	0.019	-0.255	0.111
Heat Pump Dryer	0.005	0.040	0.002	0.014	0.002
Insulation	0.126	0.847	0.031	0.113	0.044
Rooftop Solar	0.028	0.754	0.086	0.608	0.031

Conclusion

This study demonstrates that established air quality and health impact modeling processes can be used to quantify the avoided health impacts and costs of electrification at the community scale. The results show that the quantified health benefits are of a meaningful magnitude—comparable to modeled annual bill savings—including more than $250 in avoided health costs per heat pump and residential insulation retrofit. In addition, by incorporating the emissions and benefit per ton health impact factors into our building-level modeling and leveraging the wealth of data in ResStock's housing stock database, the savings estimates can be used to target retrofits in the cities and segments of the housing stock where they'll have the most impact. We can provide the modeling to governments interested in quantifying the health impacts of decarbonization actions in their jurisdictions and community health advocates interested in ways to improve outdoor air quality and health in their communities.

Further research in this area will focus on:

- **Vehicle emissions**. Using data from NEI and the EPA, the estimation of emissions factors and benefit per ton factors for fossil fuel combustion in on-road vehicles is already underway. We will explore how more robust and granular vehicle travel data can be used to construct localized health impact estimates for replacing gasoline-burning vehicles with electric vehicles.
- **Refinement of electricity demand modeling.** The current modeling distributes electricity demand and generation equally over the entire eGRID subregion for each household, assuming that the electricity demand is being met from the entirety of the grid subregion. Future iterations could model demand being met from nearby electricity generation units.

- **Demographics.** Further exploration into the varying health impacts across demographic segments, including race and income level, can yield insights into how to construct equitable electrification policies and help community advocates and policy makers gain a better understanding of the environmental justice dimensions of electrification.
- **Comparing pollutant concentrations to acceptable levels.** Certain counties nationwide are not in attainment with pollutant concentration levels required by the Clean Air Act. Future analysis could demonstrate for which counties electrification measures could reduce ambient pollutant concentrations to a level in compliance with federal regulations.
- **Community mapping.** The building-level modeling can be aggregated at different geographic levels, combined with additional sociodemographic spatial data, and displayed in a mapping tool made available to community organizations and the public. The interactive tool would allow users to explore connections between building electrification and other indicators of interest in their communities.

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