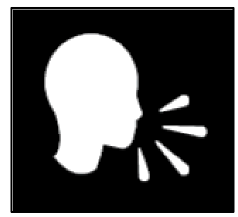
Enhancing Health Benefits of Residential Energy Efficiency Programs



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A Health Impact Assessment

SFDPH Environmental HEALTH
improving environments protecting health

Contributors

- Rajiv Bhatia designed and supervised this study with the support of Edmund Seto
- Rajiv Bhatia, Tim Choi, Solange Gould, and Shayla Livingston all contributed to the literature review for this study
- Tim Choi, Solange Gould, and Shayla Livingston conducted the analysis for this study
- Julian Bedoya, Michael Harris, Phil Martien, Jennifer MacLaughlin, Lindsey Realmuto, Meg Wall, and Tom Rivard contributed the environmental data for San Francisco used in the analysis
- Rajiv Bhatia and Tim Choi wrote the report narrative.

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Suggested Citation

Disclaimer:

The views expressed herein do not necessarily reflect the official policies of the City and County of San Francisco, the Centers for Disease Control and Prevention, or the University of California at Berkeley; nor does mention of these organizations imply their endorsements.

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Summary

Improving household energy efficiency is a federal policy priority that reduces dependence on non-renewable energy, benefits the environment, and reduces household energy bills. Public programs, at the local, state, and federal level, that subsidize energy performance of residential dwellings have the potential to improve home quality and public health, addressing such issues as indoor air quality, noise, heat, and dampness. While residential energy efficiency programs allow for building code requirements and other regulatory compliance, there is a wider range of opportunities to leverage energy efficiency investments for health.

Using environmental quality and housing data available for the City and County of San Francisco, this health impact assessment (HIA) evaluated how varying ambient air pollutant levels affect health outcomes. Additionally, the HIA evaluated the health benefits of complementary design elements—filtered mechanical ventilation and building envelope acoustical improvements. This HIA estimated benefits in terms of changes in premature mortality associated with ambient $PM_{2.5}$ exposure and subjective annoyance associated with ambient noise.

We estimate that energy efficiency upgrades alone contribute to a modest 4% reduction in deaths attributable to ambient $PM_{2.5}$ exposure (102 versus 106 excess deaths over 25 years per 10,000 households). We estimated that energy efficiency upgrades with the addition of filtered mechanical ventilation reduce indoor $PM_{2.5}$ further and result in a 47% reduction of excess deaths (57 deaths over 25 years per 10,000 households). Mortality attributed to $PM_{2.5}$ is higher in areas of San Francisco with $PM_{2.5}$ concentrations above 10 μg/ m^3 (319 excess deaths over 25 years per 10,000 households). We estimate that standard energy efficiency programs would reduce this burden of $PM_{2.5}$ on mortality only modestly (304 versus 319 excess deaths per 10,000 households over 25 years). Targeting subsidies to high $PM_{2.5}$ zones along with additional ventilation elements would reduce $PM_{2.5}$-attributable deaths by 47% (162 excess deaths per 10,000 households over 25 years).

Noise can impact human health and wellbeing through multiple, well-documented pathways. In San Francisco, we estimate about 15% of the population is currently negatively impacted by ambient noise levels. The expected benefit of standard energy efficiency protocols on the proportion of residents who are noise-affected is modest (9% versus 15%). The addition of acoustical protections reduces the percent of residents, which are noise-affected to 3%. The estimated proportion of noise affected in high $PM_{2.5}$ areas is 27%. Targeting the energy efficiency program to these areas would result in more significant reductions in the proportion of the population who are noise-affected (16% versus 27%). The addition of acoustical protections such as double-paned windows further reduces the proportion of noise affected to 7%. Targeting energy efficiency programs to areas with higher noise or air pollution is also likely to have a restorative justice effect.

The addition of an indoor air quality element such as filtered mechanical ventilation to an energy efficiency upgrade can be significant, even in a city with relatively good air quality like San Francisco, when measured in mortality cost avoided (MCA), our unit of economic value. Untargeted and receiving an energy efficiency upgrade, one homeowner over 25 years would obtain $3,776 in MCA (Table 5). The package of energy efficiency upgrade plus ventilation would merit $41,748 in MCA. By targeting to a high $PM_{2.5}$ area, a homeowner's MCA over 25 years would be $12,579 and $132,291 for an energy efficiency upgrade and energy efficiency upgrade plus ventilation, respectively. The targeted energy

efficiency upgrade plus ventilation ($132,291) is significantly better than the untargeted energy efficiency upgrade ($3,776) by a factor of 35. Since we assume the most robust package of energy efficiency upgrades and ventilation to cost $40,000 per home over 25 years, we consider the $132,291 in MCA a good value. We expect cities with greater levels of air pollution than San Francisco to have proportionally greater impacts.

The principle recommendations for Energy Efficiency Program Design based on this HIA include:

- ✓ Modify the design of existing energy efficiency programs to **allow preferential targeting of program subsidies to geographical areas with relatively higher levels of ambient air pollution and ambient noise**.

- ✓ Augment the components of energy efficiency programs to include design elements for protecting or improving indoor air quality (IAQ) and reducing the transmission of sound from outdoors to indoors. Specific elements could include:
    - **indoor air filtration**
    - **mechanical fresh air ventilation systems**
    - **local exhaust ventilation for natural gas stoves-and bathrooms and building envelope acoustical protections** (e.g., insulation, double-paned windows with air gap, caulking and sealing of all cracks and gaps, etc.).
- ✓ **Balance energy efficiency losses from operating ventilation systems with $PM_{2.5}$ removal rates and noise impacts**. It may be difficult to reach the same amount of home energy savings with the recommended home energy upgrade policy changes, as filtration and ventilation systems have energy costs and contribute to indoor noise.

Such policy changes would not only efficiently leverage energy efficiency subsidies for public health priorities but also respond to environmental quality disparities that exist among neighborhoods in the United States.

Abbreviations

CDC, Centers for Disease Control and Prevention; DOE, U.S. Department of Energy; EPA, U.S. Environmental Protection Agency; ERF, Exposure Response Function; HIA, Health Impact Assessment; HUD, U.S. Department of Housing and Urban Development; IAQ, Indoor air quality; MCA, Mortality Cost Averted; SFDOE, San Francisco Department of the Environment; SFDPH, San Francisco Department of Public Health; SFHIP, San Francisco Home Improvement Performance Program; WAP, Weatherization Assistance Program

Key Words
Energy Efficiency; Green Economy; Green Building; Health Impact Assessment; Indoor Environmental Quality; Noise; Air Pollutants

I. Background

A. Introduction and Purpose

Improving home energy efficiency reduces dependence on non-renewable energy, benefits the environment, and reduces household energy bills. Public programs, at the local, state, and federal level, to subsidize energy performance of residential dwellings also have the potential to improve home quality and public health, addressing such issues as indoor air quality, noise, heat, and dampness. While residential energy efficiency programs allow for building code requirements and other regulatory compliance, there is a wider range of opportunities to leverage energy efficiency investments for health.

Minimizing the health impact of urban air and noise pollution and achieving environmental justice are well-established priority public health objectives. In many urban areas, there exist significant disparities in urban air pollution and noise exposures associated with significant health consequences. Low-income and vulnerable populations often live disproportionately in places with unhealthful exposures to environmental agents. Targeting energy efficiency programs in higher pollution areas and augmenting these programs with health-protective design elements thus might be an effective and cost-efficient strategy for mitigating environmental health impacts and improving environmental justice.

The purpose of this assessment is to evaluate means to better integrate the objective of human health protection into the design of publically supported home energy efficiency assistance programs. Specifically, the analysis addresses two specific policy questions:

- What is the value added in terms of health outcomes of spatially targeting energy efficiency programs in areas with poor ambient air quality or high noise?
- What is the value added in terms of health of adding high-efficiency filtered ventilation and acoustical protection design elements along with energy efficiency upgrades?

B. Policy Context

Residential buildings consume 22% of all energy in the United States (U.S. Department of Energy 2011). Americans spend $230 billion each year on home energy, with low-income households spending a disproportionately larger share on energy bills (DOE 2011). Improving residential energy efficiency is a key strategy to address several public policy priorities, including reducing national dependence on fossil fuels, impact on the environment, and household energy expenses. Both DOE and Housing and Urban Development (HUD) support residential building energy efficiency through subsidies, training, workforce development, and other strategies. In California, over 50 incentives and policies promote residential energy efficiency (Database of State Incentives for Renewables and Efficiency 2012).

Recently, supporters of energy efficiency programs have begun to consider how physical and structural changes to the home may affect the health of occupants. The design and implementation of energy efficiency programs has potential to affect human health through several mechanisms, including by modifying indoor air quality, temperature, moisture, and reducing the effect of exterior noise on the indoor environment. *Healthy Indoor Environment Protocols for Home Energy Upgrades*, produced by the U.S. Environmental Protection Agency (EPA 2011) presents both a set of minimum health protections that should be included with the implementation of residential energy efficiency upgrades and additional actions to improve health conditions. Most of the minimum protections reflect existing home safety regulatory requirements and DOE's Weatherization Assistance Program (WAP) has revised its *Health and Safety Program Guidance* to be consistent with the EPA protocols.

Additional opportunities also exist to better integrate health into the design of energy efficiency programs. Specifically, there may be potential to target programs to places or populations to maximize health protections and co-benefits and add health-supporting design elements.

What is an Energy Efficiency Upgrade?

Today's energy efficiency upgrades go far beyond "weatherizing your home" of the 1970s and early 1980s consisting of low-cost caulking and weather-stripping of doors and windows. The "whole-house" building performance approach means upgrading the building envelope and/or installing or repairing heating, cooling, electrical systems, and appliances to maximize energy efficiency as a system. A work plan includes an energy audit followed by selection of comprehensive upgrades and installation done by building professionals. The average cost of one type of energy efficiency program, DOE's WAP program, is $6,500 per home. While technology, policy, and the market rapidly change the residential energy efficiency field, consumers always aspire for maximizing energy and dollar savings (DOE 2012).

Energy Audit: A set of tools used to obtain baseline energy efficiency metrics in the home. Pre-installation health and safety checks are performed. The blower door test, thermal imaging camera test, duct blaster test, and computer modeling can be used to contribute to select upgrade options.

Upgrade Options: A variety of upgrade options (Appendix 1) are available, depending on household budget and rebates. Weather-stripping doors and caulking air gaps remain the most cost-effective interventions, but upgrading water heaters, installing improved wall insulation, and energy efficient windows are becoming more common as part of energy efficiency upgrades.

C. The Nexus between Energy Efficiency, Home Design, and Health

Temperature (Thermal Comfort)

Thermal comfort is critical to wellbeing, function, and health. Exposure to cold environments impairs physical and mental function, and may cause or contribute to hypothermia or death. Physiological consequences of prolonged exposure to hot environments include impaired mental and physical functioning, dehydration (from sweating), electrolyte imbalance, and hyperthermia and may be manifest as heat exhaustion, heat syncope (fainting), heat cramps, heat stroke, and death. Humans regulate body temperature through blood flow to the skin, sweating, and breathing. The elderly and children have reduced ability for thermoregulation and several common medical conditions and therapies interfere with thermoregulation. Environmental factors contributing to thermal comfort and thermal stress include outdoor temperature, indoor temperature, humidity, temperature of surrounding environments (e.g., walls, windows, floors, furnaces), and airflow. ASHRAE Standard 55 outlines the range of temperature for human comfort. Residential building or housing codes provide enforceable standards for minimum but typically not maximum indoor temperatures. Energy efficiency can increase the efficiency and effectiveness of heating and cooling thereby increasing thermal comfort for residents and reducing the risks of thermal stress. On the other hand, in buildings without adequate cooling or ventilation systems, limiting heat loss might lead to uncomfortably high or unsafe temperatures.

Moisture

Dampness and the growth of mold is a widely prevalent building condition related to the quality of construction, the adequacy of ventilation and heating systems. The prevalence of dampness or fungi in U.S. houses has been estimated to be as high as 50% (Mudarri and Fisk 2007). Indoor dampness or mold can be associated consistently with increased asthma development and exacerbation of asthma, dyspnea, wheezing, coughing, respiratory infections, bronchitis, allergic rhinitis, eczema, and upper respiratory tract symptoms in both allergic and non-allergic individuals (Mendell 2011). One analysis estimated that “building dampness and mold are associated with approximately 30-50% increases in a variety of respiratory and asthma-related health outcomes (Fisk 2007). Furthermore, indoor dampness can support bacterial growth and contribute to infestations of house dust mites, cockroaches, and rodents. Building design features necessary to prevent moisture and mold include adequate local and general ventilation and adequate moisture barriers at the building’s envelope.

Figure 1. Common air leaks in a home (EPA 2009).

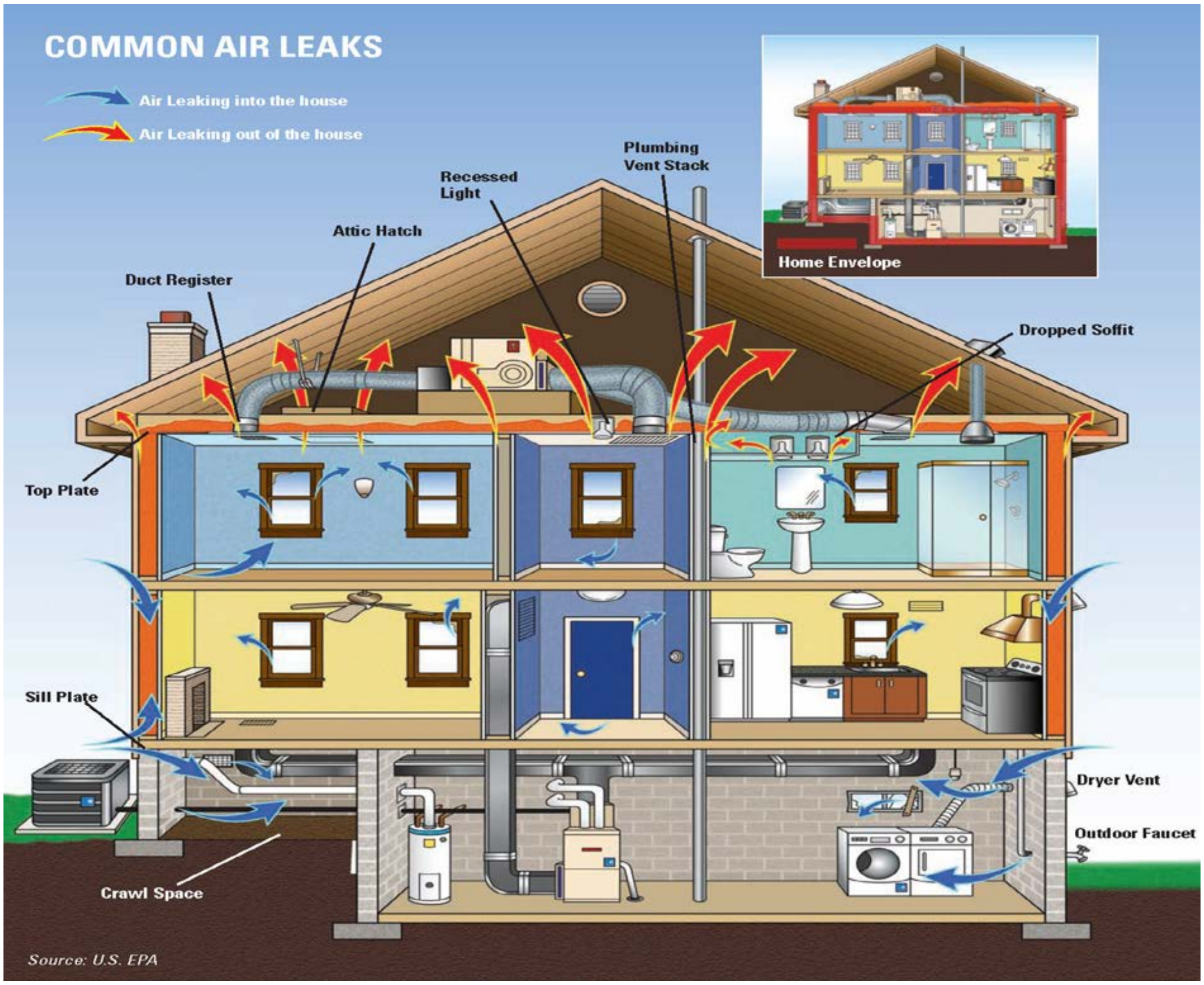
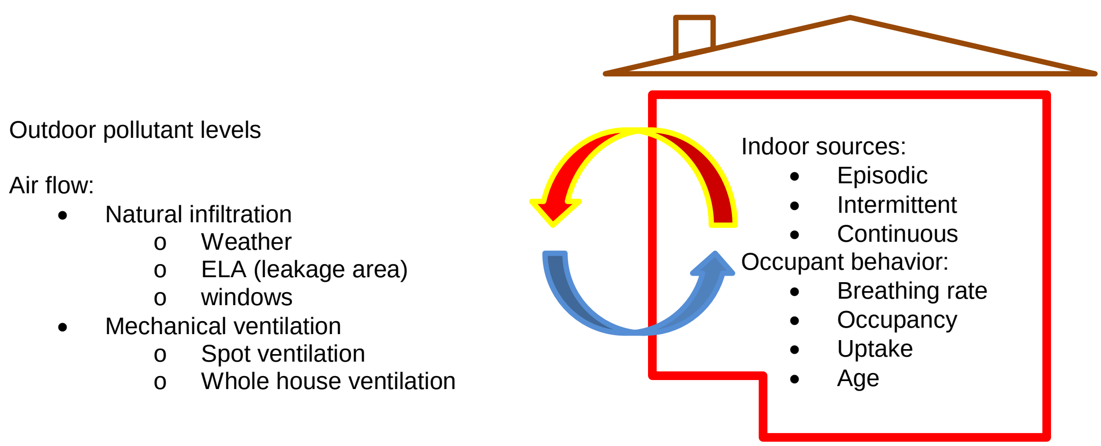


Figure 2. Factors determining indoor pollutant concentrations and exposures and the exchange between indoor and outdoor air quality (adapted from Logue and Singer, 2011)



Indoor Air Quality

Indoor air quality is a function of the emissions of chemical and biological air pollutants indoors, the infiltration of outdoor pollution indoors, the fresh airflow, and the presence of air filtration. The typical U.S. resident spends 70% of the time in residences meaning that pollutants indoors can result in significant exposure burdens (Klepeis et al., 2001; U.S. Census Bureau 2010).

$PM_{2.5}$ is one ambient air pollutant with infiltration indoors and well-established causal relationships to premature mortality and cardiovascular disease (EPA 2009). Studies based on residential location have found that children living in proximity to freeways have increased prevalence of and morbidity from asthma (Kim 2008). Infiltration of $PM_{2.5}$ from outdoor to indoor air varies widely and is related to building construction and design (Figure1 and 2; Allen 2012). Among several health-relevant pollutants measured in indoor air, $PM_{2.5}$ appears to have the greatest adverse impact on human health estimates (Figure 3; Logue et al., 2011).

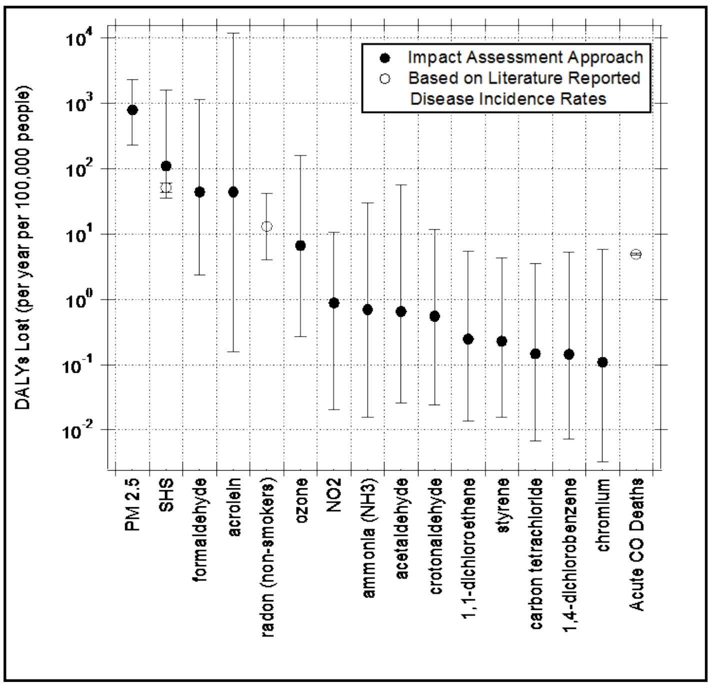


Figure 3. Estimated population-averaged annual cost in disability-adjusted life years (DALY) of chronic air pollutant inhalation in U.S. homes. Results for 12 pollutants with highest median DALY loss estimates (Logue et al., 2011).

Environmental tobacco smoke is a significant chemical contaminant in indoor air in households where smokers smoke indoors. Other chemical sources of indoor air pollution include carpeting, paints, and furnishings. Biological allergens, such as mold spores, dog and cat dander, dust mite and cockroach antigens, which are triggers for allergic disease and asthma, are equally important determinants of indoor air quality (Breysse 2004).

Energy efficiency strategies can affect both the infiltration of outdoor air pollutants indoors and the removal of indoor air pollutants. Reducing the infiltration of outdoor air could have significant health benefits in areas with compromised outdoor air quality. On the other hand, reducing fresh-air ventilation rates could limit the removal of indoor air pollutants. Generally, increasing fresh air ventilation likely benefits health by removing pollutants and controlling moisture (Sundell 2011; Seppanen 2004; Howden-Chapin et al., 2007; Sublett 2009). Filtering indoor air and filtering fresh air has potential to both reduce infiltration of outdoor air and remove indoor pollutants (Fisk 2001). Ensuring adequate fresh air ventilation and increasing the level of filtration are two design strategies that could be leveraged through energy efficiency programs to improve indoor air quality and health (National Center for Healthy Housing).

Noise

While individuals may react to noise differently, the source, intensity, duration and context of sound can impact human health and wellbeing in multiple ways. Even moderate levels of noise can impair carrying out basic day-to-day functions like sleeping, resting, concentrating on office tasks and having a normal conversation with a friend.

Sufficient scientific evidence documents that chronic exposure to moderate levels of noise, even below levels required for mechanical damage to hearing, can result in other health and physiological impacts including cognitive impairment, decreased school performance, sleep disturbance, and hypertension and ischemic heart disease (de Kluizenaar 2009). Noise annoyance is "a feeling of resentment, displeasure, discomfort, dissatisfaction, or offense when noise interferes with someone's thoughts, feelings, or actual activities" (Passchier-Vermeer et al., 2000). Numerous well-designed studies also show that children exposed to chronic transportation noise have deficits in school performance and educational outcomes (Shield 2003). As a physiological stressor that affects the autonomic nervous system and the endocrine system, noise may harm the cardiovascular system. Substantial emerging evidence links traffic noise to hypertension and ischemic heart disease (Babisch 2008) and higher rates of myocardial infarction than in the general population (van Kempen 2002). Researchers performed a meta-analysis and found a dose-response function between increasing noise levels > 60 dBA and cardiovascular risk (Babisch 2008) while in a separate study, researchers noted an increased risk of hypertension at > 64 dBA (Bodin 2009).

In urban areas, roadway vehicles are typically the single largest contributor to urban environmental noise (Dora et al., 2000; Seto et al., 2007). Mechanical equipment such as ventilation systems on rooftops is another common source of urban noise. bus traffic), increasing the distance from the source to the noise receptor (limit housing near busy roadways) or limiting the transmission of sound energy to the noise receptor from the source (sound walls; building envelope acoustical insulation). Building design solutions include mechanical ventilation to reduce the need to open windows and doors, improving wall insulation, installing double-paned windows with optimal air gaps, installing storm windows and doors and sealing and caulking all openings around electrical cables, water and gas pipes (Berendt et al., 1978).

Fire and Life Safety

An estimated 15,000 emergency room visits and 500 unintentional deaths are reported per year due to non-fire-related CO poisoning. Smoke and carbon monoxide (CO) alarms are inexpensive tools that significantly reduce the risk of injury and death from a fire (Aherns 2011). Energy efficiency professionals should readily install these devices in the context of energy efficiency programs. CO alarms add quality assurance controls when energy efficiency upgrade interventions include tune-ups to indoor combustion appliances like furnaces (DOE 2010; CDC 2005).

Household Income Sufficiency

The average household spends around 4% of their monthly income on energy; however, low-income households spend 17% (Power 2008). Subsidies for energy costs for low income families can reduce the risk of underweight children (Frank et al., 1996), suggesting that households may make tradeoffs with heat and food, commonly known as the "heat or eat" dilemma (Bhattacharya et al., 2003). Energy efficiency retrofitting can significantly reduce client heating bills, supporting the sufficiency of household income.

D. Recent Progress in Integrating Healthy Housing and Energy Efficiency Strategies

The DOE allows programs that implement energy efficiency subsidies to use funds to address issues related to health and safety. Nationally, the EPA published *Healthy Indoor Environment Protocols for Home Energy Upgrades*, and put forward minimum health protections that should be included with residential energy upgrades and additional actions to improve health conditions. A number of these minimum protections underscore existing regulatory requirements. To ensure consistency with EPA protocols, DOE's WAP Program revised its Health and Safety Program Guidance.

Several cities have been further experimenting with how to implement energy efficiency programs in ways that improve health. In San Diego, the Environmental Health Coalition has integrated lead poisoning prevention, safe and healthy housing, energy efficiency, and retrofitting in their Home Safe Home Project. Tenants in low-income communities are given recommendations to make their homes safer, healthier, and more energy-efficient. Landlords are urged to choose green and healthy property maintenance methods to maintain their properties after lead abatement and energy retrofits have been completed. Weather stripping at doors, caulking around windows, and sealing holes and cracks hinders the ability of pests like roaches and rodents to enter the home, helps protect against temperature fluctuations in summer and winter, and reduces moisture build-up within walls.

Several cities are looking for ways to ensure energy efficiency programs benefit tenants in multi-unit housing barriers by incentivizing upgrades for landlords of multi-unit dwellings in which tenants pay utility bills (eliminating the efficiency incentive for the owners). For example, Oakland has designed model tenant-landlord agreements so that all parties equitably share the costs and benefits of energy efficiency upgrades. The Cities of Berkeley, Oakland, and Emeryville are experimenting with deploying energy efficiency funding to multi-unit housing. The idea is to expand the benefits of energy efficiency to buildings where landlords have few incentives to improve efficiency, and tenants have little control.

In San Francisco, a recent law requires new residential developments located near busy transportation corridors to assess air pollution and to design ventilation systems to remove > 80% of ambient $PM_{2.5}$ from habitable areas of dwelling units. The "Reducing Traffic Pollutants in Homes Near Freeways" pilot project, also in San Francisco, is evaluating improvements that reduce infiltration of traffic-related PM in existing homes. Following a home evaluation, designers will select from a menu of interventions, including tightening the building envelope and installing local exhaust ventilation to reduce emissions from gas stoves and moisture from shower rooms. Pre- and post-testing of indoor air quality will measure the effectiveness of the remediation offered.

II. Scope and Methods

Using the City and County of San Francisco as a case study, this analysis aimed to quantify the benefits of enhancing residential energy efficiency programs with either improvement to ventilation systems or improvements to acoustical performance, comparing the benefits of these integrated strategies with typical energy efficiency strategies. We also examined the relative benefit of targeting programs to areas with higher levels of ambient air pollution.

A. Current Program Description

The San Francisco Home Improvement and Performance Program (SFHIP) , managed by the San Francisco Department of Environment (SFDOE), coordinates up to $8,500 per home to perform home energy upgrades that improve the energy efficiency, comfort, and health of residential homes. Current eligibility requirements include owning a single family home in San Francisco and being a Pacific Gas and Electric (PG&E) customer. Renters or multi-unit housing dwellings are not eligible to participate in this program. To enroll in the program, households must have an energy audit and achieve a 15% energy efficiency improvement based on a "before and after" model done by the contractor (selected from pre-approved SFDOE contractor list).

Table 3. Financial Incentives Available through SFHIP (Amounts subject to change depending on availability).

Description	Amount	Notes
SFHIP	$1,000 to $2,000	$2,000 is available to those whose income is below 120% Area Median Income (AMI). All others are eligible for $1,000. Make home at least 15% more energy efficient.
Energy Upgrade California	$2,000 to $4,000	Make home at least 20% more efficient to receive $2,000. Each additional 5% in efficiency earns another $500 up to $4,000.
Federal Efficiency Tax Credits	$1,500	
CA Appliance Rebates	Up to $1,000	
Total possible	$8,500	

B. Assessing Existing Conditions

This analysis first provides an assessment of existing programs in relationship to known environmental conditions and health needs. Using geographic information systems, we overlay the location of residences receiving energy efficiency upgrades upon measures of environmental quality (levels of particulate matter and ambient noise), measures of socio-economic status (median household income), and measures of respiratory illness (e.g. asthma hospitalization) and mortality.
We utilized the Sustainable Communities Index for San Francisco as a source of existing conditions data for environmental, health, and socio-economic conditions (http://www.sustainablesf.org/).

C. Estimating the Effects of Energy Efficiency Program Design on Health Effects Attributable to Ambient Air Pollutants

Figure 4 presents the general causal pathway used for estimating the impacts of energy efficiency upgrades on health that are mediated via ambient air pollutants. Energy efficiency upgrades have the potential to reduce the infiltration of ambient pollutants from outdoors to indoors by tightening the building envelope. If energy efficiency upgrades reduce fresh air ventilation, it may also result in an increase of air pollutants with indoor sources. Separate from standard energy efficiency upgrades, high-efficiency air filtration can remove both pollutants introduced from outdoor "fresh air" sources and remove pollutants from indoor sources. Point-source ventilation systems such as stove hoods and bathroom ventilation systems can also be components of a comprehensive energy efficiency strategy that can reduce air pollutants from the indoor environment.

Figure 4. Pathway from energy efficiency upgrades to indoor air quality (IAQ) health impacts

Energy Efficiency Upgrade Policy Alternatives	**Indoor Air Quality Factors**	**Health Impacts**
• (Untargeted) energy efficiency upgrade • (Untargeted) energy efficiency upgrade + ventilation • Targeted + energy efficiency upgrade • Targeted + energy efficiency upgrade + ventilation	• Infiltration of $PM_{2.5}$ from outdoors • Emission of chemical and biological pollutants indoors (e.g., tobacco smoke, carpeting, mold spores, cockroach antigens, dust mites, etc.) • Fresh air flow • Presence of air filtration	• Asthma • Allergies • Extreme weather-related morbidity and mortality • Cardiovascular disease • Chronic obstructive pulmonary disease

Indoor air quality is associated with multiple health endpoints. This analysis focused on one relationship between a pollutant and a health outcome—the change in premature mortality associated with changes in indoor $PM_{2.5}$ from outdoor sources. Ambient $PM_{2.5}$ pollution is prevalent nationally, and concentrations often exceed health protective standards. Exposure disparities exist within most urban areas. $PM_{2.5}$ has an established cause and effect relationship to premature mortality. Exposure occurs both indoors and outdoors; indoor exposure is modifiable through building design, such as through the use of mechanical ventilation and filtration systems.

We assessed the mortality benefits associated with energy efficiency interventions using the following four steps:

1. Estimate the existing attributable burden of pre-mature mortality from $PM_{2.5}$ for each residential parcel.
2. Estimate the current condition and change in indoor $PM_{2.5}$ concentration associated with energy efficiency upgrades, adding ventilation, for each household.
3. Estimate the relative change in time-weighted daily $PM_{2.5}$ exposure for household members.
4. Apply the relative change in $PM_{2.5}$ exposure to the existing burden of $PM_{2.5}$ on mortality.

We also applied a monetary valuation to deaths avoided that are attributable to $PM_{2.5}$.

Step 1

Estimate the existing attributable burden of pre-mature mortality from $PM_{2.5}$ for each residential parcel

Epidemiological studies along with data on pollutant exposure, population size, and mortality rates provide data to construct exposure-response functions relating exposure to ambient $PM_{2.5}$ and premature mortality. We estimated the impact of energy efficiency upgrades with and without filtered mechanical ventilation on changes in indoor $PM_{2.5}$ exposure and associated related premature mortality using a standard exposure response function (equation 1).

$$\text{(1) Attributable Deaths}_{PM\ 2.5} = (RR_{PM\ 2.5} - 1) * I_O * P_{exp}$$

Where:

- $RR = e^{(-\beta * \delta\ PM2.5)}$ estimate of the relative risk of the incidence of mortality in a population exposed to a particular increment of $PM_{2.5}$ above background levels
  - o β = coefficient of $PM_{2.5}$ parameter in regression model
- I_O = crude mortality incidence rate
- P_{exp} = size of the population experiencing a change in exposure

Several well-designed, peer-reviewed prospective cohort studies conducted in the U.S. general population provide data for the effect of long-term community-level $PM_{2.5}$ exposures on community-level annual mortality rates (Table 1). These EPA uses these studies for regulatory impact assessments because of their geographic scope and their extensive reexamination (Industrial Economics 2006 and 2010). Lower risk estimates in the American Cancer Society (ACS) cohort relative to the Harvard Six Cities study may be due to higher population socio-economic status or exposure misclassification from retrospective exposure assessments. A re-analysis by Jerrett et al. (2005) of an ACS subpopulation in Los Angeles, using more spatially refined intra-regional exposure data to reduce exposure misclassification, found a higher central relative risk estimate of 1.17 in the same cohort.

Table 1. Long Term Prospective Cohort Studies of Chronic Exposure to $PM_{2.5}$ and Mortality

Cohort/ Publication	Population	RR per 10 µg/m^3 $PM_{2.5}$ (95% Confidence Interval)
American Cancer Society Pope (Pope 2002)	USA, 51 cities Adults, Age > 30 years	1.06 (1.02-1.11)
Harvard Six Cities (Lepeule 2012)	USA, Multiple Cities General Population	1.14 (1.07, 1.22)
American Cancer Society (Jerrett 2005)	USA, Los Angeles General Population	1.17 (1.05 -1.30)

Our impact assessment utilized the ERF from the recent extended re-analysis of the Harvard Six Cities study for (RR=1.14 per 1 µg/m^3 $PM_{2.5}$) for predicting $PM_{2.5}$ attributable health impacts in San Francisco. The California Department of Public Health provided all-cause mortality incidence data at the zip-code level for the City and County of San Francisco. We estimated the residential population exposure to ambient $PM_{2.5}$ at each residential lot using results from dispersion models described above and the ArcGIS zonal statistics spatial analysis tool using residential lots as the “zones.” We estimated the population of each residential lot based on the population of the census block and the particular lot's share of the block's total residential building area and height. We applied equation (1) above for the population, exposure, and baseline mortality rate of each lot. We then aggregated the population exposed and estimated excess annual premature deaths for exposure categories.

Step 2

Estimate the current condition and change in indoor $PM_{2.5}$ concentration for various scenarios

The EPA Steady-State Mass Balance Equation provided a way to estimate indoor residential concentrations of $PM_{2.5}$ considering effect of infiltration and ventilation on the concentration of outdoor $PM_{2.5}$ indoors. This equation (2) estimates the indoor concentration of $PM_{2.5}$ as a function of the outdoor concentration, the building's air exchange rate (AER), and the natural fallout rate. The equation assumes that there are no indoor sources of $PM_{2.5}$.

$$\text{(2) } C_{\text{Indoor PM 2.5}} = (AER * 0.95)/(AER+0.27) * C_{\text{Outdoor PM 2.5}}$$

Where

- 0.27 is a constant representing the indoor $PM_{2.5}$ fallout rate in 1/hours
- 0.95 is a constant representing the $PM_{2.5}$ penetration coefficient (unit-less)
- AER = Normalized Leakage (NL) * Weather Effects
  - o Weather effects = 0.92 for all locations in San Francisco
  - o Normalized Leakage = $\exp^{(9.63 + (-0.00503 * \text{Year Built}) + (-0.00269 * \text{Square Meters})}$ (Chan et al., 2003).

To apply the impact of an energy efficiency upgrade on a home, we used equation (3) but assumed 20% less normalized leakage (Berry and Brown 1994; Sherman and Dickerhoff 1998):

$$\text{(3) } C_{\text{Indoor PM 2.5}} = (AER * .80 * 0.95)/(AER+0.27) * C_{\text{Outdoor PM 2.5}}$$

Finally, we modified equation (4) to account for the impact of a HEPA (high-efficiency particle arrestance) filtered mechanical ventilation unit (Macintosh et al., 2008) on an energy efficiency upgraded home resulting in:

$$\text{(4) } C_{\text{Indoor PM 2.5}} = (AER * .80 * 0.95)/(AER+0.27 +2.4) * C_{\text{Outdoor PM 2.5}}$$

Utilizing the above equations and estimates of ambient $PM_{2.5}$, we estimated indoor $PM_{2.5}$ for each residential parcel in San Francisco. Data from the San Francisco Assessor provided information on the year of the dwelling and its floor area. We excluded buildings by size (≥ 279 m^2 or 3000 ft^2) and year built (≤ 1906) to follow the normalized leakage (NL) model parameters applied by Chan et al. (2003). To estimate the time-weighted exposure, we applied equation 5.

Step 3

Estimate the relative time-weighted change in exposure to ambient $PM_{2.5}$

Human exposure to ambient air pollution occurs both outdoors and indoors in residences as well as non-residences. Thus, exposure varies by the $PM_{2.5}$ concentration in different locations and the time spent in those locations. To estimate the impacts of energy efficiency upgrades and ventilation enhancements, we constructed a time-weighted exposure measure using typical time-activity patterns (Echols et al., 1999; Klepeis et al., 2001) in four locations—indoor residence (69%), indoor office, factory, or school (5%), indoor restaurant or retail (13%), and outdoor general or driving (13%) in equation 5.

$$\text{(5) Exposure}_{PM2.5\ TWA} = C_{Residential\ PM\ 2.5} \times T_{Indoor\ home} + C_{Non\text{-}Residential\ PM\ 2.5} \times T_{Indoor\ office,\ factory,\ or\ school} + C_{Non\text{-}Residential\ PM\ 2.5} \times T_{Indoor\ restaurant} + C_{Non\text{-}Residential\ PM\ 2.5} \times T_{Outdoor\ general,\ driving}$$

We assumed 16.56 hours for indoor residence, 1.2 hours for indoor office, factory, or school, 3.12 hours for indoor restaurant, and 3.12 hours outdoor general or driving over a 24-hour period. We calculated $PM_{2.5}$ for indoor residence using the outdoor $PM_{2.5}$ at that residential lot as a starting point (equation 2). We assumed a fixed $PM_{2.5}$ for indoor office, factory, or school of 7.2 (Burton et al., 2000; EPA 2000), indoor restaurant or bar of 9.0 (Ott et al., 1996) and outdoor city general of 8.4.

Step 4

Apply the time-weighted exposure changes to the existing the burden of mortality attributable to $PM_{2.5}$

We applied the relative change in time-weighted exposure to $PM_{2.5}$ and then calculated the proportional change in premature mortality attributable to $PM_{2.5}$ for each residential lot selected.

Using the above stepwise approach, we estimated the aggregate benefit on premature mortality of both the current energy efficiency program and an energy efficiency program with filtered (MERV-13) mechanical ventilation. We compared these design options for actual residential parcels participating in the 2010-2012 San Francisco residential energy efficiency upgrade program, for randomly selected households, as well as for households in areas of the city with PM2.5 concentration estimates above 10 $\mu g/m^3$. For comparability, we presented our findings in terms of benefit over 25 years per 10,000 homes under each targeting scenario:

Monetary Valuation

We estimated the economic value of reductions in mortality using the EPA's standard value of a statistical life (2006) adjusted to 2012 dollars to be $8,456,372/death.

D. Estimating the Effects of Energy Efficiency Program Design on Health Effects Attributable to Ambient Noise

Figure 5 shows the pathway used for estimating the impact of energy efficiency program design on noise attributable health impacts. The design of energy efficiency upgrades can have an impact on the building shell and affect the indoor acoustical environment. Tightening the building envelope with complementary interventions in heating, ventilation, and air conditioning, can reduce the need to open windows, thereby reducing the intrusion of ambient noise. Reducing exposure to noise potentially results in improvements in outcomes such as sleep, cognitive function, and stress. Ambient noise levels have a well-established exposure-response relationship with several health outcomes.

Figure 5. Pathway from energy efficiency upgrades to interior noise health impacts

Energy Efficiency Upgrade Policy Alternatives	Indoor Noise Factors	Health Impacts
• (Untargeted) energy efficiency upgrade • (Untargeted) energy efficiency upgrade + acoustical improvements • Targeted + energy efficiency upgrade • Targeted + energy efficiency upgrade + acoustical protection	• Ambient noise levels (road, air and rail traffic, mechanical point sources, etc.) • Indoor noise sources • Noise reduction caused by building envelope • Interior construction	• High annoyance • Hypertension • Cognitive impairment • Cardiovascular impacts

We utilized the following definition of noise annoyance: "a feeling of resentment, displeasure, discomfort, dissatisfaction, or offense when noise interferes with someone's thoughts, feelings, or actual activities" (Passchier-Vermeer et al., 2000). We quantified the benefits of alternative designs of energy efficiency programs annoyance related to noise using the following steps:

1. Estimate ambient sound levels at all residential parcels in San Francisco.
2. Estimate the change in outdoor to indoor sound levels under alternative program design scenarios.
3. Estimate health effects by assessing burden of annoyance and stratify by target areas.

<u>Step 1</u>

Estimate the ambient sound levels at the facades of all parcels in San Francisco

We estimated 24-hour (L_{dn}) and daytime (L_{day}) ambient sound levels using the Federal Highway Administration's (FHWA) traffic noise model (FHWA 2004, Seto et al. 2007). Model inputs included traffic volumes by time of day, vehicle type (car, truck), and traffic speeds. Traffic also included existing estimates of bus volume. We assigned the proportion of trucks that were heavy versus medium trucks based on neighborhood-level estimates on arterial versus non-arterial streets using aerial photography (Holt et al. 2009).

Managing the outputs of the noise model in ArcGIS, we estimated the ambient sounds at each residential façade, a standar exposure measure in epidemiological studies on noise. We performed an overlay in ArcMap 10 of all residential parcels, rasterized ambient noise, and $PM_{2.5}$ levels and extracted this information to obtain parcel locations and corresponding $PM_{2.5}$ and ambient noise levels.

Step 2

Estimate the attenuation of ambient noise indoors for alternative energy efficiency designs

We estimated applied sound transmission class (STC)[1] for both standard construction and alternative energy efficiency designs based on research of residential building interventions and acoustics. This factor represents of the expected attenuation of ambient noise indoors, For example, where the ambient sound level is 70 dBA Ldn, the indoor noise level of a standard home is expected to be 55 dBA based on a STC (attenuation) of 15 dB (Janssen 2012). Based on the literature we estimated the attenuation in an energy efficiency upgrade home to be 21 dB and the attenuation in an energy efficient home with additional acoustical protection to be 30.

Table 2. Estimated Cumulative Noise Attenuation for Alternative Energy Efficiency Program Designs

STC	Type of Package	Description
15	Typical home (pre-retrofit)	• Light-frame exterior shell • Single-paned windows (closed) • Customary air and noise leaks
21	Energy efficiency upgrade (standard)	• Duct sealing • Thermal insulation of walls • Air sealing of customary air leaks
30	Energy efficiency upgrade + acoustical improvements	• Double-paned windows (sound rated, air-tight seal) • Storm windows (with rubber gaskets) • Solid core doors • Install/upgrade central heating and A/C to reduce need to open windows

Sources: Berendt 1978, San Diego (City of) 2008

Step 3

Estimate effects of alternative program designs on subjective annoyance

Miedema (2001) pooled 45 international studies relating 24-hour noise levels and self-rated noise annoyance and used these pooled data to develop ERFs for annoyance from road, railroad, and aviation noise. Equation (5) below estimates the proportion of the population reporting high levels of noise annoyance based on the 24-hour sound level (L_{dn}) for road traffic noise. This function applies to a range of exposure from 42 dBA to 75 dBA.

(5) $\% \text{ High Annoyance} = 9.994 * 10^{-4} (L_{dn} – 42)^3 – 1.523 * 10^{-2} (L_{dn} – 42)^2 + 0.538 (L_{dn} – 42)$

Using this exposure response function (ERF), one can estimate the proportion of residents expected to be highly annoyed by noise for 1 dB sound level increments from 42dBA to 75dBA. The ERF parameter is the 24-hour average ambient/exterior sound level; to estimate the effect of building acoustical intervention, we assumed it reflected “typical home” building design and treated the difference between the standard construction attenuation and the attenuation under alternative design strategies as an equivalent reduction in the parcel-level ambient sound level.

[1] STC, or sound transmission class, is a common measurement of decibel reduction of a partition or building material such as windows, walls, and doors averaged over multiple frequencies. If the STC of a product is high, the product will be better able to reduce noise. The limitation of STC is that it does not consider frequencies below 125 Hz, some of this being traffic-related noise or rumbling bass from a car. Most acoustical engineers advise caution when looking solely at STC and advise relying on real-world testing of products, if and when available.

Using the modeled parcel-level ambient sound level and the attenuation factors, we estimated the proportion of noise-affected residents under existing conditions, for the current energy efficiency program and for a modified energy efficiency program additional acoustical protections. We compared these design options for the actual residential parcels participating in the 2010-2012 San Francisco residential energy efficiency upgrade program, for randomly selected households, for households in areas of the city with PM2.5 concentration estimates above 10 μg/m^3, and finally , for households in areas with sound levels above 60 dBA Ldn. For comparability, we presented our findings in terms of benefit per 10,000 households. We also assumed an average household size of 2.26 (U.S. Census 2010).

Limitations to the Scope of this HIA

- Our analysis focuses only on one pollutant and one health outcome related to indoor air quality, likely underestimating the benefit of energy efficiency improvements on health. For example, we did not consider indoor sources of $PM_{2.5}$ and other indoor pollutants (e.g., from cooking, using harmful household cleaners, etc.).

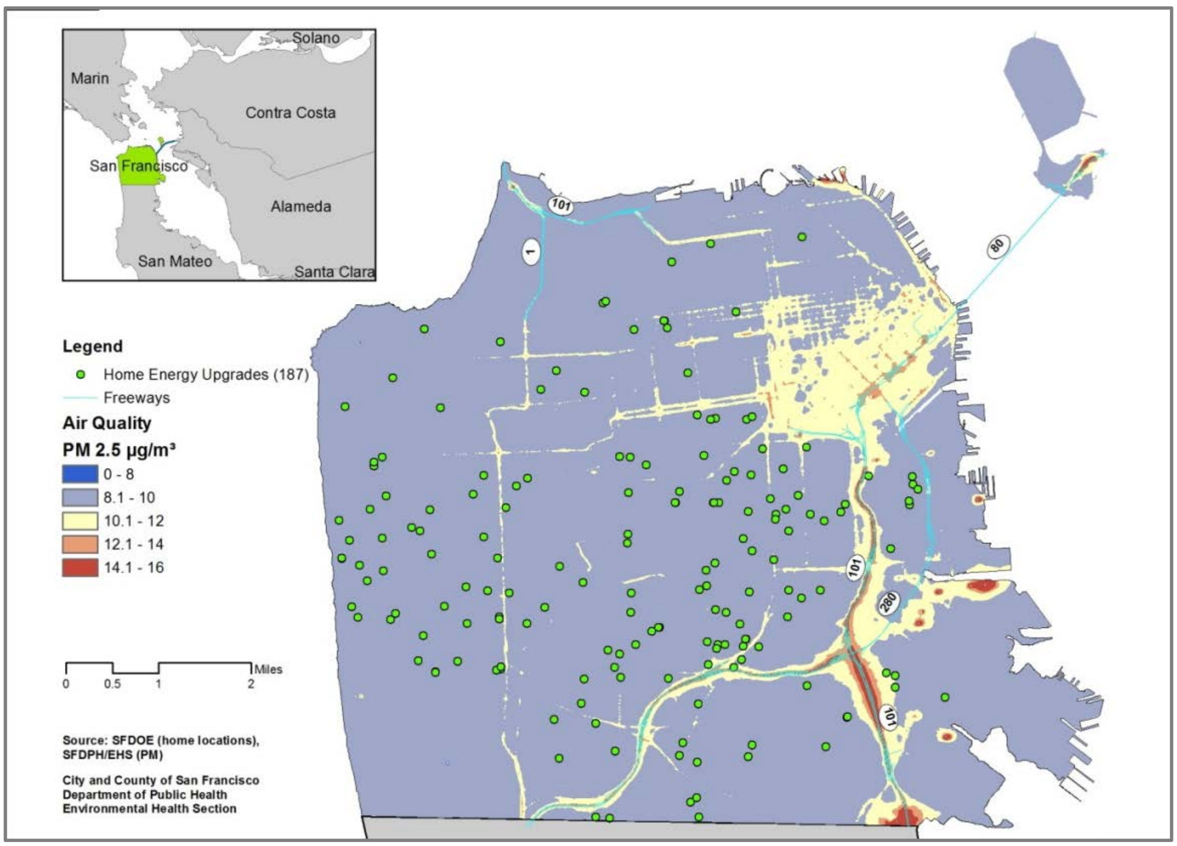
- We did not address how alternative program design (e.g. the inclusion of mechanical ventilation) would affect household energy consumption.

III. Findings

A. Existing Conditions

Map 1 below shows that homes that have already benefited from energy efficiency subsidies have been in locations with relatively low levels of ambient $PM_{2.5}$. In San Francisco, higher $PM_{2.5}$ areas are those in closer proximity to highways and the port. Research in California shows that members of racial or ethnic minority groups and people of low socioeconomic status are more likely to live near busy roads and to be exposed to higher concentrations of traffic related air pollutants (Gunier et al., 2003). Research has documented diverse adverse health outcomes associated with residential proximity to traffic, including asthma (Gauderman et al., 2005), low birthweight (Wilhelm et al., 2003), cardiovascular disease (Künzli et al., 2010), and premature mortality (Jerrett et al., 2009).

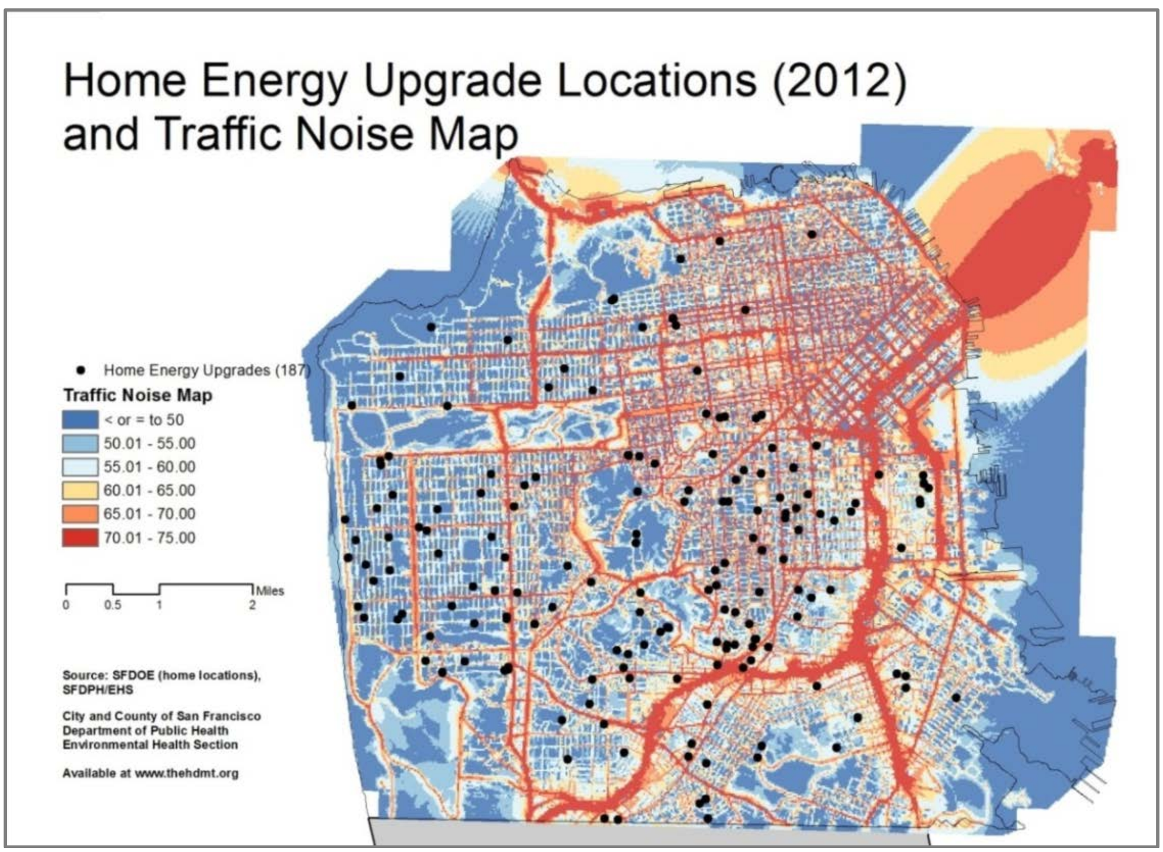
Map 1. SFHIP Energy Efficiency Upgrade Locations and Average Annual PM2.5 Concentration from All Sources (µg/m3)



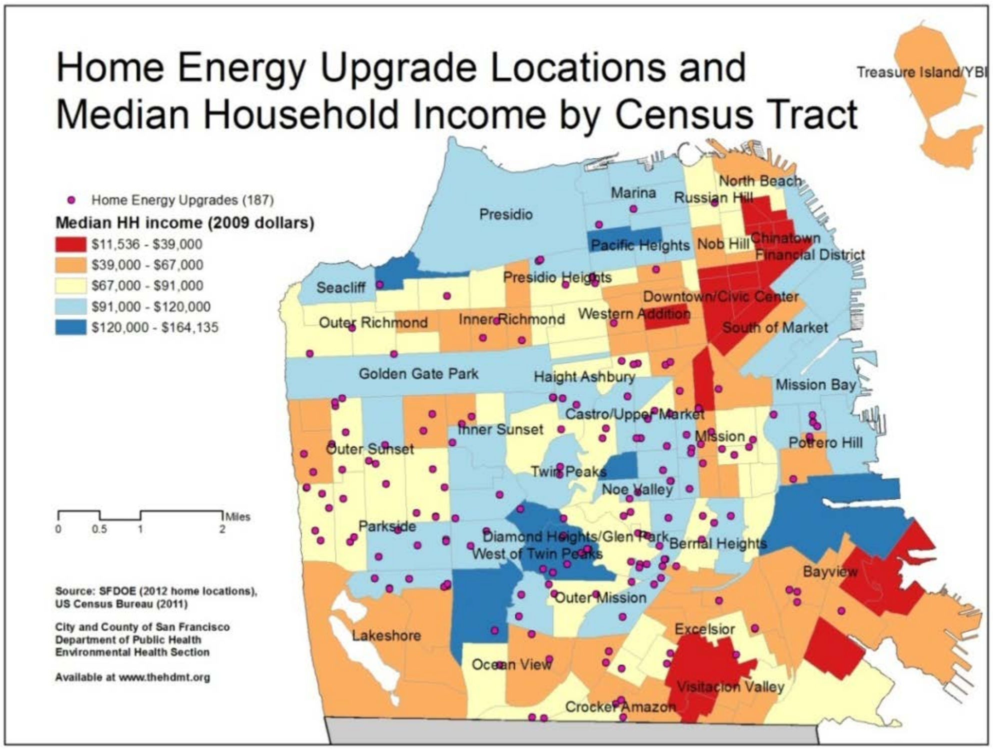
Map 2 (traffic noise) shows high noise (>= 60 dBA) areas of San Francisco and SFHIP energy efficiency upgrade locations. Map 2 similarly illustrates that most residences receiving SFHIP incentives were located in areas with relatively lower ambient noise levels. One explanation for these relationships is that the SFHIP program benefits single-family dwellings and not multi-family dwellings. Residential density is associated with higher noise, more traffic, and lower area-level income in San Francisco, particularly the northwest quadrant. The health effects of traffic noise levels shown on Map 2 can be understood using WHO guidelines for community noise levels (Appendix 2; WHO 1999). For example, humans require additional vocal effort to communicate when the ambient noise level is about 65 dBA. High noise areas nearly completely overlap areas with high concentrations of $PM_{2.5}$ (Map 1), illustrating that elevated ambient noise is a more prevalent environmental exposure than high $PM_{2.5}$ exposures.

Maps 3, 4, and 5 illustrate that households which have benefited from energy efficiency subsidies have been disproportionately located neighborhoods with higher median household incomes (Map 3) and with relatively lower rates of asthma hospitalizations (Map 4) and premature mortality (Map 5). Among neighboring Bay Area counties, San Francisco death rates are lower than those of Alameda or Contra Costa counties, but higher than those of Marin, San Mateo, or Santa Clara counties. The leading cause of death in San Francisco for 2000-2007 is ischemic heart disease for which $PM_{2.5}$ is a known contributing cause.

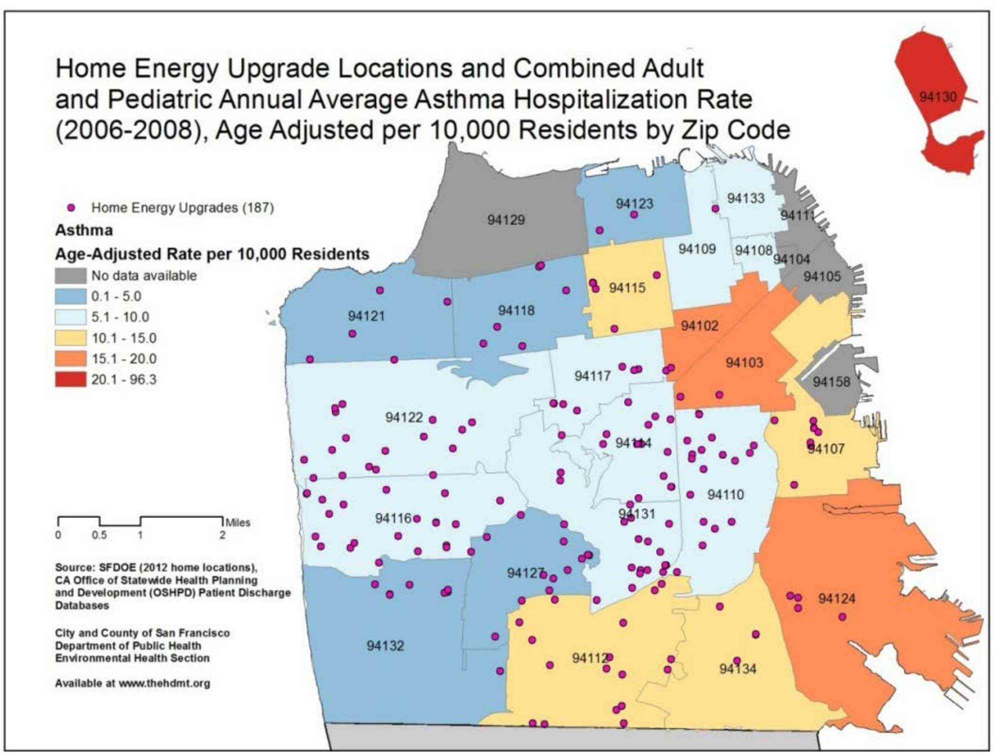
Map 2. SFHIP Energy Efficiency Upgrade Locations and Traffic Noise Map



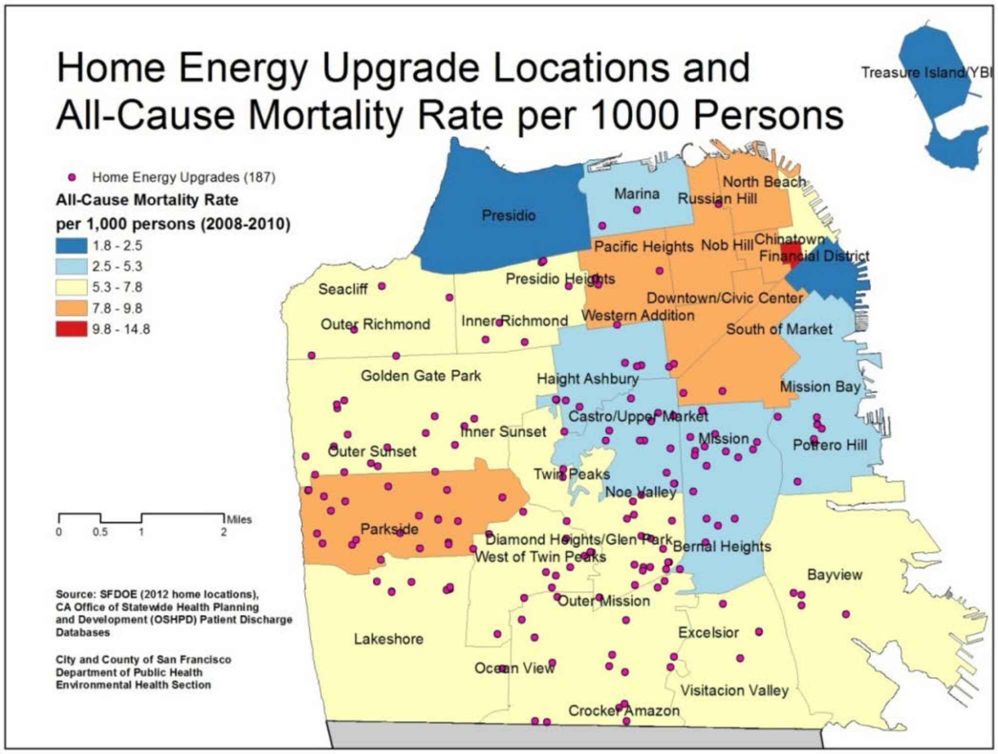
Map 3. SFHIP Energy Efficiency Upgrade Locations and Median Household Income



Map 4. SFHIP Energy Efficiency Upgrade Locations and Asthma Hospitalization Rates



Map 5. SFHIP Energy Efficiency Upgrade Locations and All-Cause Mortality Rates



B. Impacts of Energy Efficiency Program Alternatives on $PM_{2.5}$ Attributable Mortality

Each year, we estimate that exposure to ambient $PM_{2.5}$ results in 94 early deaths annually citywide. This statistic translates into 96 excess deaths per 10,000 households over a period of 25 years. Table 4 provides our estimates of the differences in excess deaths per 10,000 households over 25 years for alternative designs for energy efficiency programs considering both additional ventilation elements to reduce infiltration of $PM_{2.5}$ and targeting the program to areas with $PM_{2.5}$ concentrations above 10 $\mu g/m^3$.

Table 4. Estimated Mortality Attributable to $PM_{2.5}$ Exposure Under Current Conditions, Energy Efficiency Upgrade, and Energy Efficiency Upgrade + Ventilation Protections

Geographic Targeting Areas	Number of Households	Number of Persons	Deaths Attributable to $PM_{2.5}$ Exposure over 25 years per 10,000 households		
			Current Conditions	+ Energy Efficiency Upgrade	+ Energy Efficiency Upgrade plus Ventilation
All Households	103,160	343,627	96	92	51
SF Energy Efficiency Program - Untargeted	187	686	106	102	57
$PM_{2.5}$ > 10	569	2,324	319	304	162

Benefit of adding filtered mechanical ventilation to energy efficiency programs

The data suggest that homes that have participated in the SFHIP program are in areas with $PM_{2.5}$ concentrations slightly more than the median level of the city. We estimate that energy efficiency upgrades alone contribute to a modest 4% reduction in deaths attributable to ambient $PM_{2.5}$ exposure (102 versus 106 excess deaths over 25 years per 10,000 households). We estimated that energy efficiency upgrades with the addition of filtered mechanical ventilation reduce indoor $PM_{2.5}$ further and result in a 47% reduction of excess deaths (57 deaths over 25 years per 10,000 households) compared to current conditions.

Benefits of targeting energy efficiency programs to high air pollution exposure areas

As expected, mortality attributed to $PM_{2.5}$ is higher in areas with $PM_{2.5}$ concentrations above 10 $\mu g/m^3$ (319 excess deaths per 10,000 households over 25 years). We estimate that standard energy efficiency programs would reduce this burden of $PM_{2.5}$ on mortality only modestly (304 versus 319 excess deaths per 10,000 households over 25 years); however, targeting subsidies to high $PM_{2.5}$ zones along with additional ventilation elements would reduce $PM_{2.5}$-attributable deaths by 47% (162 excess deaths per 10,000 households over 25 years).

Table 5 summarizes the effects on premature mortality attributable to $PM_{2.5}$ of modifying the design of energy efficiency programs in terms of their likelihood, magnitude, severity, and distribution. Overall, there is a high likelihood that either targeting or adding ventilation elements would reduce premature mortality. The magnitude of the benefit of targeting is small relative to the benefit of additional ventilation elements in the San Francisco context, owing to the small range of $PM_{2.5}$ levels observed in San Francisco. Targeting would contribute to a restorative equity effect.

Table 5. Energy Efficiency Upgrade Policy Health Effects Characterization: $PM_{2.5}$ and Premature Mortality

Health Effects: Characteristics	Interpretation	Characterization
Likelihood	How certain will the energy efficiency program policy under study affect $PM_{2.5}$ related premature mortality, irrespective of the frequency, severity, or magnitude of the effect?	**Very Likely/Certain**: Consistent evidence for causality from epidemiologic studies with diverse populations, pollution mixes, and exposure range, as well as evaluation studies of $PM_{2.5}$'s effect.
Severity	How significant is premature death with regards to human function, well-being or longevity, considering the affected community's current ability to manage the health effects?	**High:** The impacts on $PM_{2.5}$ are associated with reductions in mortality.
Magnitude	How much will $PM_{2.5}$-attributable premature deaths change as a result of the change in design of energy efficiency programs?	Adding ventilation elements to energy efficiency programs would have **moderate health benefit.** Targeting energy efficiency alone would have **limited health benefit**; however, targeting plus additional ventilation elements would have a **significant** benefit.
Distribution	Will health effects be distributed equitably across populations?	Untargeted energy efficiency programs with or without ventilation enhancements may disproportionately benefit wealthier residents and owners of single-family homes. Targeting energy efficiency programs to high air pollution areas is likely to have restorative justice effect.

C. Economic Value of $PM_{2.5}$ Related Health Benefits

Applying the monetary value of a statistical life utilized by the EPA in risk assessment, we estimated the economic value of targeting energy efficiency upgrades and ventilation programs to high $PM_{2.5}$ zones in San Francisco to be $132,291 (per household over 25 years). Excluding ventilation enhancements would yield only a fraction of that amount--$12,579 in mortality cost avoidance. We estimate the cost of the energy efficiency and ventilation improvements at $40,000 per household over 25 years.

Table 6. Estimated Mortality Cost Avoided (MCA) Attributable to $PM_{2.5}$ Exposure under Energy Efficiency Upgrade, and Energy Efficiency Upgrade + Ventilation Protections (2012 $). There are no MCA under Current Conditions.

Program Scenario	Per 10,000 Homes		Per Single Home	
	MCA for Energy Efficiency Upgrade over 25 years	**MCA for Energy Efficiency Upgrade + Ventilation over 25 years**	**MCA for Energy Efficiency Upgrade over 25 years**	**MCA for Energy Efficiency Upgrade + Ventilation over 25 years**
SF Energy Efficiency Program - Untargeted	$ 37,755,047	$ 417,484,450	$ 3,776	$ 41,748
All Households	$ 36,405,714	$ 379,986,425	$ 3,641	$ 37,999
$PM_{2.5}$ > 10	$ 125,785,974	$ 1,322,912,409	$ 12,579	$ 132,291

D. Analytic Uncertainties and Limitations: $PM_{2.5}$ Attributable Health Effects

The quantitative analysis of the magnitude of the impacts on $PM_{2.5}$ attributable mortality includes a number of assumptions and parameters with uncertainty as summarized in Table 7. These uncertainties informed the level of confidence of the health effect characterization summarized in Table 5 above.

The precision of our analysis depends on both in the accuracy of the $PM_{2.5}$ exposure data and the exposure-response function (ERF). The Bay Area Air Quality Management District (BAAQMD) and SFPDH produced estimates of $PM_{2.5}$ concentrations using inventories of know sources and computer dispersion modeling. The model has not been validated with field measure, but the modeling technique is routinely used in regulatory decision-making worldwide.

The ERF for $PM_{2.5}$ exposure and pre-mature mortality is based on epidemiological studies conducted in diverse contexts. Epidemiological studies that form the basis of our ERF account for socio-economic factors including poverty, education, and type of employment that may confound the effect of $PM_{2.5}$ on mortality. Scientific evidence has not established a threshold below which effects of $PM_{2.5}$ on mortality do not occur. Nevertheless, the range of exposure in our analysis is within the range of the studies used to define a E-R relationship for $PM_{2.5}$. For all of these reasons, the ERF should be applicable to the San Francisco context.

Notably, our analysis applies epidemiological studies based on inter-regional differences in pollutants to within-region concentration differences. Some have argued that ERFs based on inter-regional studies may under-estimate the slope of the concentration-response relationship (Jerrett 2005).

We assume changes in exposure to ambient $PM_{2.5}$ indoors can be translated to a change in the overall effect of ambient $PM_{2.5}$ on health. This appears to be a logical but untested assumption. We attempt to account for cumulative exposures to ambient $PM_{2.5}$ (indoor home, indoor office, indoor restaurant, outdoors) by using a time-weighted formula for daily exposure.

In order to contribute to our original research questions, it was necessary to assume uniform conditions among diverse building types in San Francisco.

Table 7. Magnitude of the Estimated Health Effects for Traffic-related $PM_{2.5}$ and Premature Mortality: Uncertainty Factors

Factors Affecting Certainty	Assessment Approach	Summary Confidence Level
Exposure Assessment	Widely used method for dispersion modeling not validated by local measures. Parcel level assignment and time-weighted exposure defensible. Could not account for heterogeneity in other exposure factors by population and location.	Moderate
Baseline Disease Prevalence	Mortality Rate: County-level data from vital statistics.	High
Exposure-Response Function (ERF)	ERF generalizable to US city and exposure range	Moderate

E. Impacts of Energy Efficiency Policy: Noise-related Annoyance

In San Francisco, we estimate 14% of the population in San Francisco is currently negatively impacted by ambient noise levels based on the well-established empirical relationship between ambient noise levels and subjectively assessed noise annoyance. Table 8 illustrates the benefit of energy efficiency programs and the potential benefits of additional noise protection elements on the prevalence of noise-affected in the population. Table 8 further illustrates the effect of targeting the program to areas with high $PM_{2.5}$ (> 10 µg/m^3) as well as targeting to high levels of ambient noise (=> 60 dBA).

Table 8. Proportion of residents subjectively annoyed by noise under alternative energy efficiency program designs

Program Scenario	Current Conditions		Standard Energy Efficiency Program		Energy Efficiency Program + Acoustical Protections	
	Proportion noise-affected	Number noise-affected per 10,000 households	Proportion noise-affected	Number noise-affected per 10,000 households	Proportion noise-affected	Number noise-affected per 10,000 households
Random San Francisco Households	14%	3268	8%	1758	2%	543
SF Energy Efficiency Program – Current experience	15%	3320	9%	1950	3%	715
High $PM_{2.5}$ => 10	27%	6080	16%	3712	7%	1630
High Noise (=> 60 dBA, LDN)	21%	4823	13%	2896	5%	1209

Benefits of adding acoustical protection elements to energy efficiency programs

In San Francisco, we estimate that currently about 15% of the population in San Francisco is negatively impacted by ambient noise levels. The expected benefit of standard energy efficiency design elements on the proportion of residents who are noise-affected is modest relative to current conditions (9% versus 15%). The addition of acoustical protections reduces the percent of residents, which are noise-affected to 3%.

Benefits of targeting energy efficiency programs to high pollution areas

The estimated proportion of noise affected in high $PM_{2.5}$ areas is 27%. Targeting the energy efficiency program to these areas would be expected to result in a more significant reductions in the proportion of the population who are noise-affected (16% versus 27%). The addition of acoustical protections such as double-paned windows further reduces the proportion of noise affected to 7%.

Table 9 summarizes the effects on the proportion of noise-affected residents of modifying the design of energy efficiency programs in terms of their likelihood, magnitude, severity, and distribution. Overall, there is a high likelihood the addition of acoustical protections or targeting would lead to reductions in the proportion of noise-affected. The magnitude of the health benefit is significant both for additional acoustical elements and for targeting. Targeting energy efficiency programs to areas with higher noise or air pollution is likely to have a restorative justice effect.

Table 9. Energy Efficiency Upgrade Policy Health Effects Characterization: Traffic-related Noise Health Effects

Health Effects: Characteristics	Interpretation	Characterization
Likelihood	How certain energy efficiency program or additional acoustical protections will change health effects related to noise irrespective of their severity or magnitude?	**Very Likely/Certain for Annoyance:** Consistent evidence for causality from epidemiologic studies with diverse populations, noise levels, and exposure ranges.
Severity	How important is the effect on noise related annoyance with regards to human function, well-being or longevity, considering the affected community's current ability to manage the health effects?	**Medium:** Acute, chronic, or permanent effects that substantially affect function, well-being, or livelihood but are largely manageable within the capacity of the community health system.
Magnitude	How much will noise related annoyance change as a result of the energy efficiency program design alternatives under study?	Health benefits of additional acoustical protections are **moderate**. A health benefit of targeting energy efficiency is also **moderate.**
Distribution	Will the effects be distributed equitably across populations?	Targeting the program would have **restorative** equity Effects:

F. Analytic Uncertainties and Limitations: Noise-related Health Effects

There exists a high level of strength and consistency in the evidence relating ambient noise to perceived noise annoyance. Studies of the effect of noise on annoyance are consistent across international contexts. Our ERF for perceived noise annoyance is based on a meta-analysis of 24 international studies that include the exposure range in San Francisco.

We have high-moderate confidence in our estimated ambient noise levels based on the FHWA traffic noise model (Table 9). Modeled values are highly consistent with field measures of noise collected in San Francisco.

We assume a standard acoustical attenuation of 15, 21, and 30 db for the standard, energy efficiency upgrade and energy efficiency upgrade + acoustical improvements, respectively based on the best available knowledge. These standardized STC values do not account for the heterogeneity of residential construction and how this heterogeneity relates to the spatial variation in ambient noise.

Our analysis focuses on a limited set of noise-related health outcomes, likely underestimating the benefit of energy efficiency upgrades and acoustical improvements on health. Utilizing 24-hour measure of noise does not allow us to account for effects of single noise events (e.g., the passage of an ambulance at night or garbage collection in the morning). We did not account for individual behavior factors that will affect noise levels (e.g., opening windows). We also did not consider how changes to ventilation systems might contribute to more noise in the interior environment.

Table 9. Uncertainty Factors Regarding the Magnitude of Estimated Health Effects of Noise

Factors Affecting Certainty	Assessment Approach	Summary Confidence Level
Exposure Assessment	Model for estimating ambient sound levels validated with field measures. Residential facade noise estimation not validated.	High-Moderate
Baseline Disease Prevalence	Baseline prevalence of noise annoyance unavailable but not required for exposure response function.	N/A
Exposure-Response Function (ERF)	Community annoyance ERF based on pooled analysis of multiple studies in diverse contexts. ERF specific to road traffic noise sources.	High (Community annoyance)

IV. Recommendations

The benefits of home energy efficiency upgrades have historically centered on the environment, energy efficiency, and household financial savings. This section provides recommendations for energy efficiency programs to increase their health co-benefits. We recognize that few of the potential health effects of energy efficiency programs have been evaluated with observational studies. Such research would further inform program design.

Our analysis suggests that we can significantly improve health-related indoor environmental quality by targeting energy efficiency programs to high air pollution areas and adding enhanced indoor air quality and acoustical protection design elements to the standard energy efficiency protocols. Furthermore, targeting is a potential strategy to address the historic legacy of environmental justice in disproportionately exposed neighborhoods.

Recommendations for Energy Efficiency Program Design

- ✓ Modify the design of existing energy efficiency subsidy programs **to allow environmental heath based targeting of program subsidies, particularly in geographical areas with relatively higher levels of ambient air pollution and ambient noise.**

- ✓ Augment the components of energy efficiency programs to include design elements for protecting or improving indoor air quality (IAQ) and reducing the transmission of sound from outdoors to indoors. Specific elements could include:
  - **indoor air filtration**
  - **HEPA filtered mechanical ventilation systems**
  - **local exhaust ventilation for natural gas stoves and bathrooms and building envelope acoustical protections** (e.g., insulation, double-paned windows with air gap, caulking and sealing of all cracks and gaps, etc.).
- ✓ **Balance energy efficiency losses from operating ventilation systems with $PM_{2.5}$ removal rates and noise impacts.** It may be difficult to reach the same amount of home energy savings with the recommended home energy upgrade policy changes, as filtration and ventilation systems have energy costs and contribute to indoor noise.

Recommendations to facilitate and evaluate program design enhancements

- ✓ **Ensure collaboration** between lead program designers and implementers of energy efficiency programs and health agencies **to maximize health benefits**. Ensure that energy efficiency programs fully consider health benefits by integrating metrics such as estimated mortality avoided, related monetary savings, and noise annoyance reduced. Limiting the benefits of energy efficiency retrofits to energy and household financial savings underestimates the significance of energy efficiency as a health issue.

- ✓ **Monitor energy efficiency savings** before and after energy efficiency upgrade to ensure estimated energy savings meet or exceed actuals. Complete **rigorous quality control** for one year (accounting for seasonal variation) after completion of energy efficiency upgrades in the event that energy savings fail to meet estimates. Residents should receive appropriate energy efficiency education and understand the effects of using common household cleaning products, changing air filters, leaving windows open for ventilation or smoking indoors.

- ✓ **Enhance building codes** for installation and retrofitting. Equally important, ensure the energy efficiency upgrade plan, installation, and operation perform as intended. Houses are complex systems and each home retrofit is different. The interplay between the building shell, HVAC system, resident behaviors, ambient air and noise quality, among other factors, demand a balanced approach by the energy efficiency building professional—"change one, and you may inadvertently affect another."

- ✓ **Increase awareness of program resources** among all stakeholders**,** especially among low-income and minority populations of available energy efficiency programs. Property managers and residents should also be educated on how their behavior affects energy efficiency.

Funding Strategies that May Facilitate Health-based Targeting and IAQ and Acoustical Design Elements

- ✓ **Increase financial resources from public and private sources** available for retrofit programs. The $1.6 billion per year (2009-2011) in federal stimulus weatherization funds is unlikely to re-occur. A mobilized labor force of energy efficiency professionals along with operational lessons learned supported a massive, multi-year, nation-wide ramp-up. Drastic funding cuts would reduce the effect and potential for deep energy efficiency benefits, particularly to vulnerable populations. Congress is looking to reduce energy efficiency retrofits to funding levels not seen since 2001 to around $100 million.

- ✓ **Ensure energy efficiency programs are available for multi-unit housing.** Target owners of rent-subsidized units with energy efficiency rebates since they have little financial incentive to improve units. They are also more likely to have higher building occupancies per unit, lower socioeconomic and health status.

- ✓ **Remove or minimize barriers of high upfront energy efficiency retrofit costs incurred by the homeowner.** After the free home energy assessment, using revolving loan funds and/or on-bill financing that allows residents to pay back their energy efficiency upgrade loan incrementally on their monthly bill can be effective in breaking the stalemate of financing. Utility companies, who could pay energy efficiency contractors upfront with the homeowner's deed of trust serving as collateral, would offset their profit in energy costs with low-rate interest collected from the homeowner. The City of Portland has used this model since 2009 through Clean Energy Works Portland.

- ✓ **Streamline varied energy efficiency rebate systems** by integrating rebates on a central web portal that allows e-filing and tracking. Develop straight-forward outreach materials that target concerns of landlords and owners of residential properties on such issues as high upfront costs, uncertain financial returns, clear monthly savings vs. retrofit costs, troubleshooting issues, etc. (Burroughs and Schwartz 2012).

Additional Research that Could Inform Energy Efficiency Program Design

- ✓ **Initiate prospective cohort study using bio-markers for pre-post energy efficiency intervention**. This kind of study would contribute to a more nuanced understanding of the intersection between energy efficiency upgrades and health. These findings could inform building design and retrofit policies to realize more effective gains with precision on types of exposures and effects of human behavior.

- ✓ **Use retrofitted home directory to create indoor environmental quality alert system**. Cross-reference databases of weatherized homes (similar to Lawrence Berkeley Lab's Residential Diagnostics Database) with local emergency room records to check for indoor environment-related hospitalizations. Identify trends that might guide on-going best practices of home energy efficiency retrofits. With varied temperatures and unique vulnerabilities to climate change, locally-appropriate home energy efficiency information is needed. Data collection and analysis coupled with stakeholders' experiences should be a valuable feedback loop for improving home energy efficiency.

- ✓ **Expand environmental health based targeting criteria to include demographic and housing stock vulnerability targeting**. Use demographic (number of single family headed households, children under five, seniors, disabled, veterans, formerly homeless, etc.) and housing stock (year built, construction type, micro-climate, etc.) to assess and prioritize those groups vulnerable to energy shocks and environmental health-related morbidity and mortality.

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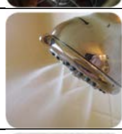
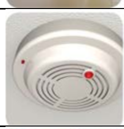
Appendices

Appendix 1.Standard energy upgrade options. Performing the cost effective measures (1-7) first is recommended (CA Energy Commission et al., 2012). Additional upgrade options are listed 8-11.

1.		Duct Sealing	Leaky ducts can lose over 20% of conditioned air through holes and poor connections. Make sure that your warm and cool air gets where it needs to go.
2.		Attic Insulation	Attic insulation keeps your house cool in the summer and warm in the winter. There are many types of insulation available, including low-emission and recycled content.
3.		Hot Water and Pipe Insulation	Insulating your hot water pipes saves energy and helps conserve water, since you won't have to run the shower or faucets as long to get the water hot.
4.		Combustion Safety Testing	Combustion safety testing ensures that all of your gas appliances are venting correctly—providing you with safety and peace of mind.
5.		Thermostatic Shower Control	A thermostatic control valve shuts off the shower once the water turns warm, in order to save hot water until you are ready to enter the shower.
6.		CO Detector	Smoke alarms and carbon monoxide detectors are a simple and cost-effective way to ensure the safety of your home and the people in it.
7.		Air Sealing	Sealing air leaks reduces drafts and keeps warm air from escaping during winter months. Combined with insulation, it is one of the most cost-effective energy savings.
8.		Energy-Efficient Cooling	Sealing, insulation, energy-efficient windows and shading can all help reduce the need to run your air conditioning. High-efficiency heating and cooling systems (HVAC) can also save significant energy.
9.		Energy-Efficient Water Heater	Energy-efficient storage water heaters and on-demand tankless heaters save energy—and can save money on heating and water bills, too.
10.		Wall Insulation	Properly insulating the exterior walls of your house increases comfort and reduces heating and cooling costs. There are a number of loose-fill and sprayed foam insulations suitable for existing walls, including recycled content and low-emission types.
11.		High-Efficiency Furnace	A high-efficiency furnace can save significant energy over older, low efficiency models. And if you complete basic sealing and insulation first, you can save money because you can reduce the size of your furnace.

Appendix 2. World Health Organization guideline values for community noise in specific environments (1999)

Specific environment	**Critical Health effect(s)**	**LAeq [dB(A)]**	**Time base [hours]**	**LAmax fast [dB]**
Outdoor living area	Serious annoyance, daytime and evening Moderate annoyance, daytime and evening	55 50	16 16	- -
Dwelling, indoors Inside bedrooms	Speech intelligibility & moderate annoyance, daytime & evening Sleep disturbance, night-time	35 30	16 8	- 45
Outside bedrooms	Sleep disturbance, window open (outdoor values)	45	8	60
School class rooms & pre-schools, indoors	Speech intelligibility, disturbance of information extraction, Message communication	35	during class	-
Pre-school bedrooms, indoor	Sleep disturbance	30	sleeping time	45
School, playground outdoor	Annoyance (external source)	55	during play	-
Hospital, ward rooms, indoors	Sleep disturbance, night-time Sleep disturbance, daytime and evenings	30 30	8 16	40
Hospital treatment rooms, indoors	Interference with rest and recovery	#1		
Industrial commercial Shopping and traffic areas, indoors and outdoors	Hearing impairment	70	24	110
Ceremonies, festivals and entertainment events	Hearing impairment (patrons: < 5times/year)	100	4	110
Public addresses, indoors and outdoors	Hearing impairment	85	1	110
Music and other sounds through headphones/ earphones	Hearing impairment (free-field value)	85 #4	1	110
Impulse sounds from toys, fireworks and firearms	Hearing impairment (adults) Hearing impairment (children)	-	-	140 #2 120 #2
Outdoors in parkland and conservations areas	Disruption of tranquility	#3		

#1: As low as possible

#2: Peak sound pressure (not LAF, max) measured 100 mm from the ear

#3: Existing quiet outdoor areas should be preserved and the ratio of intruding noise to natural background sound should be kept low

#4: Under headphones, adapted to free-field values