**Preliminary Report: Quantifying the Health Benefits of Reduced Wood Smoke from Energy Efficiency Programs in the Pacific Northwest**

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# Executive Summary

The Regional Technical Forum (RTF) investigated whether health benefits from reduced wood smoke can be directly attributed to energy efficiency program activity, and whether these benefits can be quantified and monetized given the current state of science. This report presents the RTF’s investigation of the technical basis of quantification methods, identifies the data requirements needed for analysis, and describes the uncertainties around the required data, analysis, and the results. The report also speaks to the attribution question, particularly around the quantification of the wood smoke reduction from energy efficiency program intervention. Based on this analysis, the RTF concludes that wood smoke reductions, and the resulting health effects, can be directly attributed to certain efficiency programs and that those reductions can be quantified. The range of these estimates has wide error bounds, but even at the low end the impacts of cost effectiveness would be significant for some energy efficiency measures.

### Analytical Approach

This analysis uses a ductless heat pump (DHP) program as an example to understand the extent to which the health benefits from wood smoke reduction are directly attributable and quantifiable. The primary goal of current DHP programs is to displace residential electric baseboard heating with a more efficient form of electric heat. In the Pacific Northwest, there are many electrically heated homes that use wood as a supplemental form of heating. Programs aimed at reducing electric heating may also reduce the use of supplemental wood heat. The scientific community has determined that burning wood leads to the formation of a special class of small particulate pollutants that cause respiratory, cardiovascular, and other health hazards if inhaled. In studying the link to health effects, the investigation focuses on the health impacts from the reduction of these small particles known as PM2.5—particulate matter that is 2.5 microns or less in diameter—as these are considered to be especially harmful to human health.

Estimating the monetary value of health impacts requires four steps: (1) quantifying emissions changes directly attributable to energy efficiency programs; (2) dispersion modeling; (3) estimating the health effects; and (4) monetizing the health effects. The RTF investigated each step to understand its contribution to the monetary value of a health benefit, the current state of the science and technical understanding of underlying phenomena, and the availability of data to conduct the necessary calculations.

The RTF recently approved an analysis demonstrating that homes use less supplemental wood heat after installation of a DHP providing evidence of a direct relationship. It currently includes the savings in wood purchases as part of the cost-effectiveness calculation for this measure. To conduct this analysis, the RTF used pre- and post-billing data and interview data from 3,400 homes across the region. For weatherization and other energy efficiency measures that interact with the heating system, the RTF recommends assessing the data needs for each measure on a measure by measure basis.

Dispersion modeling is a well-established science. Software packages that estimate pollutant dispersion are available, with varying level of precision and detail. The EPA continues to collect detailed data that can be used to calibrate and validate a list of approved dispersion models.

The third and fourth steps—quantifying and monetizing the health effects caused by a given pollution change—present the greatest level of uncertainty. Both steps try to quantify the cause and effect relationship that have been proven to exist, but are difficult to measure. Public health organizations have devoted extensive resources to the scientific effort and proven that a range of health effects from increase in PM2.5 pollutants can be estimated. Individual studies conducted to estimate health effects from PM2.5 generally have higher levels of uncertainty, but collectively the studies yield reasonably reliable estimates. In the final step, the most significant monetary value from health benefits (more than 98 percent) is attributed to reduced mortality, which is expressed as a value of statistical life (VSL). Although the science continues to evolve, economists have settled on a general method to estimate VSL.

While the RTF did not have access to the raw data that informs the dispersion modeling and quantification and monetization of health benefits steps, it reviewed studies and meta-analysis using that primary data, which was sufficient for this report.

### Recommendations

If the Council decides that cost effectiveness determinations should incorporate health impacts of wood smoke changes, the RTF recommends the following:

* Quantify Emission Changes: Reduction in wood use cannot be generalized across efficiency programs. Dedicated studies for different groups of measures or programs are likely required to estimate measure-specific or program-specific wood smoke reductions.
	+ The RTF would be an appropriate body to review research and data on the changes in wood use attributable to electric energy efficiency program.
	+ Energy efficiency programs, such as weatherization programs, should consider collecting survey data related to supplemental wood heat as a routine administration function.
* County-level analysis: Health effects from wood smoke are dependent on geographic factors such as the location of the reduced pollutants and population density in areas affected. Likewise, efficiency programs rarely are deployed uniformly across the region. Thus, the granularity of analysis should be at the county level in most cases.
* Dispersion Modeling: Because the total health benefit from a fixed PM2.5 decrease is proportional to the population of a county, the RTF should explore the possibility of attaining higher precision in dispersion modeling at the county level.
* Estimate Health Effects: The RTF recommends accepting the Environmental Protection Agency’s Integrated Science Assessments conclusions with respect to quantifying the epidemiological link.
* Monetize Health Effects: The value used at this step is a policy decision. The RTF would be an appropriate body to conduct sensitivity analyses on the range and interpret how those affect the cost-effectiveness of a measure.

# Introduction

The Regional Technical Forum (RTF) is a technical advisory committee to the Northwest Power and Conservation Council (Council). The Council is responsible for developing an electric power plan for the Pacific Northwest as directed by the Northwest Power Act of 1980. In developing a regional power plan, the Council analyzes the costs of electric generation and conservation resources available to meet the region’s electricity demand. Included in the cost of those resources are environmental costs and benefits that the Council determines are quantifiable and directly attributable to the resource.

The RTF is comprised of technical experts from around the region and its responsibilities include estimating the lifetime costs and savings of conservation resources. This report describes the RTF’s investigation into the feasibility of capturing, attributing, and monetizing health effects associated with a ductless heat pump (DHP) program. The primary objective is to better understand whether human health benefits (or costs) resulting from an energy efficiency measure can be isolated and quantified given the current state of the science. Using a DHP program as an example, this report investigates the technical basis of various quantification methods in use today, identifies the data requirements needed to perform an analysis, and describes the uncertainties around the data, analysis, and results.

Although any energy efficiency measure that impacts heating load could impact the use of supplemental wood heat, the RTF chose to focus its investigation on a concrete example. The RTF chose DHP because of existing data that demonstrates a direct relationship between the installation of a DHP and the reduction of supplemental wood use

## Identifying Potential Supplemental Wood Heat Savings

In 2013, the RTF developed energy savings estimates for converting residential zonal electric heating systems to DHPs based on Ecotope Consulting’s billing analysis of approximately 3,400 recent DHP installations.[[1]](#footnote-1) The analysis identified both electric and supplemental wood heat savings from DHP installation. The analysis also found that in cold climate zones, installation of DHPs saved considerably less electricity in homes with supplemental wood heat than in homes without supplemental wood heat. Evidence indicated that the savings difference was due to heating load being shifted from wood-burning appliances to DHPs in the homes with supplemental wood heat. In other words, people who used more supplemental wood heat prior to DHP installation relied on the DHP to meet a greater portion of their heating load than was met by the old electric resistance zonal heating system, and therefore relied less on the use supplemental wood heat.

Based on these findings, the RTF developed a method for estimating the amount of wood saved due to DHP installation in the three heating zones in the Pacific Northwest. These supplemental wood heat savings benefit the customer in the form of (1) reduced wood purchasing costs, and (2) possible health benefits from reduced wood smoke. While the RTF currently accounts for cost savings from reduced wood use in its cost effectiveness estimate, it does not account for any health benefits due to reduced wood smoke.

## Identifying Potential Links to Health Impacts

The scientific community has determined that burning wood leads to the formation of a special class of small particulate pollutants that cause respiratory, cardiovascular, and other health hazards if inhaled. Based on an extensive body of clinical and epidemiological research, the EPA has found that particulate matter of diameter 2.5 microns or less (PM2.5) is especially harmful to human health.[[2]](#footnote-2) “Collectively, the evidence is sufficient to conclude that the relationship between long-term PM2.5 exposures and mortality is causal.”[[3]](#footnote-3)

As a corollary to that finding, the EPA has found that health benefits realized from decreased wood smoke are attributable to reduced exposure to concentrations of PM2.5 particles that are present in the wood smoke. In addition to primary PM2.5 emissions, studies have shown that wood smoke also contains SO2, NOx, NH3, and volatile organic compounds that lead to secondary PM2.5 formation through atmospheric chemical reactions. It is important to note that the RTF reviewed and incorporates, but does not attempt to evaluate, the EPA’s findings and causal determination.

After learning of the health impact of reduced wood smoke, the RTF reviewed a back of the envelope calculation that estimated potential magnitude of the dollar value of the impact.[[4]](#footnote-4) The rough estimate was that health benefits from reduced PM2.5 in the atmosphere could be as high as $1 per kWh of wood heat avoided. Since this result is on the order of ten times the retail cost of electricity, the RTF determined it warranted further investigation.

# Initial Screening Study by Abt

To better understand the potential health impact of reducing wood smoke in the region, the RTF hired Abt Associates to perform a screening level assessment.[[5]](#footnote-5) This study was not tied to a specific energy efficiency program. Rather, the RTF used the study to better understand the order of magnitude of the potential effect from wood smoke reductions in the Pacific Northwest. Abt used the EPA’s Co-Benefit Risk Assessment (COBRA) screening model for analysis and investigated the health effects of reducing wood heat in residential single family homes in the Pacific Northwest by 25 percent, 50 percent, 75 percent, and 100 percent.[[6]](#footnote-6) Tables 1 and 2 present the results of the analysis. It is important to note that these results represent the valuation of multiple year’s health impacts due to a single year (2017) of emissions changes.

Table 1. Study-Area Health Effects from Reductions in 2017 Wood Smoke Emissions

|  |  |
| --- | --- |
| **Health Incident Avoided** | **Number of Cases Avoided** |
| **25% Reduction** | **50% Reduction** | **75% Reduction** | **100% Reduction** |
| **Adult Mortality (low)** | 55 | 111 | 166 | 222 |
| **Adult Mortality (high)** | 126 | 251 | 376 | 501 |
| **Infant Mortality** | >0 | >0 | >0 | >0 |
| **Non-fatal Heart Attacks (low)** | 6 | 12 | 17 | 23 |
| **Non-fatal Heart Attacks (high)** | 54 | 108 | 161 | 214 |
| **Resp. Hosp. Adm.** | 11 | 23 | 34 | 46 |
| **CVD Hosp. Adm.** | 14 | 27 | 41 | 55 |
| **Acute Bronchitis** | 91 | 182 | 273 | 364 |
| **Upper Res. Symptoms** | 1,664 | 3,328 | 4,992 | 6,655 |
| **Lower Res. Symptoms** | 1,165 | 2,326 | 3,485 | 4,640 |
| **Asthma ER Visits** | 24 | 48 | 72 | 95 |
| **MRAD** | 48,683 | 97,316 | 145,898 | 194,430 |
| **Work Loss Days** | 8,220 | 16,435 | 24,645 | 32,849 |
| **Asthma Exacerbations** | 1,745 | 3,489 | 5,232 | 6,975 |

Table 2. Monetized Study-Area Health Effects from Reductions in 2017 Wood Smoke Emissions

| Health Incident Avoided | Economic Value (Millions 2010$, 7% discount rate) |
| --- | --- |
|  | 25% Reduction | 50% Reduction | 75% Reduction | 100% Reduction |
| Total Health Effects (low) | $425.8 | $851.3 | $1,276.6 | $1,701.3 |
| Total Health Effects (high) | $960.9 | $1,920.0 | $2,877.5 | $3,833.3 |
| Adult Mortality (low) | $418.1 | $835.9 | $1,253.3 | $1,670.4 |
| Adult Mortality (high) | $947.4 | $1,893.2 | $2,837.3 | $3,779.7 |
| Infant Mortality | $1.1 | $2.1 | $3.2 | $4.3 |
| Non-fatal Heart Attacks (low) | $0.7 | $1.4 | $2.1 | $2.8 |
| Non-fatal Heart Attacks (high) | $6.4 | $12.8 | $19.1 | $25.4 |
| Resp. Hosp. Adm. | $0.3 | $0.6 | $0.9 | $1.3 |
| CVD Hosp. Adm. | $0.5 | $1.1 | $1.6 | $2.1 |
| Acute Bronchitis | >$0.0 | $0.1 | $0.1 | $0.2 |
| Upper Res. Symptoms | $0.1 | $0.1 | $0.2 | $0.2 |
| Lower Res. Symptoms | >$0.0 | >$0.0 | $0.1 | $0.1 |
| Asthma ER Visits | >$0.0 | >$0.0 | >$0.0 | >$0.0 |
| MRAD | $3.3 | $6.6 | $9.9 | $13.2 |
| Work Loss Days | $1.6 | $3.2 | $4.8 | $6.4 |
| Asthma Exacerbations | $0.1 | $0.2 | $0.3 | $0.4 |

The results of Abt’s study showed reducing wood smoke emissions leads to reductions in PM2.5 and thus had a positive effect on human health. As Table 2 indicates, the main driver of the monetized health benefits is the reduced risk of premature mortality among adults—the dollar value of reducing adult mortality constitutes over 98 percent of the total monetized health benefits.

The same study by Abt produced additional findings that inform this report. In particular:

* COBRA’s health effect estimates have a nearly linear relationship with changes in the ambient concentration of PM2.5. For example, the health effects from the 100 percent emissions reduction scenario are approximately double those from the 50 percent reduction scenario.
* The estimates do not exhibit any minimum PM2.5 reductionthreshold needed to generate health benefits. This reflects the current state of scientific understanding.
* EPA’s Integrated Science Assessment finds that the evidence generally supports the use of an approximately linear model, although the science does not rule out the potential for non-linear effects.[[7]](#footnote-7)
* Reductions of PM2.5 emissions in one county can affect PM2.5 levels in adjacent counties; therefore, modeling health impacts from reduced wood smoke requires consideration of geographic location of the reductions.
* For a given change in atmospheric PM2.5 concentration, the health effects are approximately proportional to the size of the exposed population.
Therefore, a small change in the PM2.5 concentration in a densely populated area can produce a large health impact.
* Adult mortality is the predominant driver of the valuation of health impacts. This is due to the associated monetary value of reducing risk of mortality.
* The study suggested the health benefit associated with displacing supplemental wood heat with a DHP was on the order of 10 times higher than the retail cost of the electricity required to run the DHP for the displacement heating. Note, the wood smoke reduction levels modeled by Abt in this study were many times higher than expected levels of wood smoke reduction associated with electric energy efficiency programs that reduce supplemental wood heat.

# Analysis of the Monetary Value of a Public Health Benefit from a Ductless Heat Pump Program

Given that the Abt study described above focused on large scale, regional reductions in wood use and the results were significant in terms of having potential to affect the cost effectiveness of energy efficiency measure, the RTF decided to further analyze the expected scale and range of the health benefits directly attributable to electric energy efficiency programs. The RTF also analyzed the status of the current science used to monetize and quantify the health effects. The RTF contract analysts performed this analysis and Abt was hired to provide feedback on the analysts’ treatment of important technical issues. This feedback has been incorporated in the present report.

For this work, the RTF followed a four step process common to most methods of estimating the monetary value of a public health benefit associated with an initiative to reduce harmful emissions (including the Abt screening study). The four steps in this process are:

1. Quantify Emission Changes: Estimate the total change in expected emissions due to the energy efficiency initiative
2. Dispersion Modeling: Use dispersion modeling to estimate the expected change in ground level pollution
3. Estimate Health Effects: Estimate the public health effect based on epidemiological research
4. Monetize Health Effects: Determine the monetary value of the estimated public health effect

This section walks through each of these steps, focusing on the example of a DHP program, and discusses the methods and associated risks and limitations that come with attempting to quantify health effects directly attributable to an energy efficiency program.

## Step 1: Quantify Emission Changes

The first step in the process is to determine whether there is a measurable, direct link between implementing an energy efficiency program and a reduction in wood emissions and, if so, how to quantify the reduction.

The RTF has adopted two separate estimates of supplemental wood heat reduction that it uses to account for cost savings from reduced wood purchases in the cost of the efficiency measure. The first estimate applies to a DHP measure and was determined using data from a NEEA DHP pilot program.[[8]](#footnote-8) For this pilot program, NEEA installed almost 3,400 DHPs in the Pacific Northwest and collected three types of data for the evaluation. These were:

* Pre- and post-DHP billing data for every home in the pilot program;
* Interview data describing wood-heat usage and house size for every home in the pilot;
* Metering data for about 100 program homes.

Using this data, the RTF estimated the percent of the heat load met with wood heat both pre and post-DHP installation. The difference between these estimates was then used to estimate the wood savings associated with DHP installation. The results are summarized in Table 3 below, and a more detailed description of the analysis is provided in Appendix A.

Note that the “wood” savings figures presented in this section—and used in the COBRA models throughout this report—actually reflect all supplemental fuels, including both propane and wood. This investigation did not include a detailed treatment of supplemental fuel mixes, but the RTF does not consider fuel mixes to be significant obstacle to quantifiability. Based on the RBSA, propane accounts for approximately 17% of the supplemental fuel burned in DHP-eligible homes. Since burning propane does not release significant quantities of PM2.5, a more detailed analysis would be expected to yield wood savings—and health benefits—that are about 17% lower than the figures that follow.

Table 3 Estimated Wood Savings from Ductless Heat Pumps

|  |  |  |
| --- | --- | --- |
|  | **Percent of load met with supplemental wood**(homes with wood heat) | **Average wood savings per DHP**(energy delivered to space, kWh equivalent) |
| Heating zone | **Pre-DHP** | **Post-DHP** | **Homes with wood heat** | **Average across all homes** |
| **1** | 27% | 3% | 2,155  |  604 |
| **2** | 48% | 36% | 1,020 |  204 |
| **3** | 36% | 18% | 2,415 | 1,690  |

The combination of billing, metering, and interview data provides strong empirical basis for demonstrating that a reduction in wood smoke can be both directly linked to implementation of an energy efficiency program and quantified. It should be noted, however, that one weakness of this analysis is the lack of a control group. It is possible that some external phenomenon that coincided with the program—such as a region-wide burn ban—that may have driven a reduction in the use of supplemental wood heat. To reduce uncertainty around these estimates, the RTF may want to consider future studies that include a control group to firm up the understanding of attribution.

The second estimate the RTF developed applies to weatherization and (ducted) heat pump measures. This estimate is based on statistical analysis of the 2012 Residential Building Stock Assessment developed by the Northwest Energy Efficiency Alliance (NEEA). The analysis determined the average fraction of heating load that is met with supplemental wood heat, and it assumes wood savings due to weatherization measures is proportional to electric savings (a detailed description of this analysis is provided in Appendix B). The RTF used this estimate to account for the reduction in wood purchases as part of the cost effectiveness of the measure. Since the RTF derived this estimate from observational data (comparing two sets of houses rather than changes for a single house), more research may be needed to meet the standard of directly attributable and quantifiable.

Next, to estimate the air quality impact of a DHP program focused on replacing zonal electric heat, the RTF used data from the Residential Building Stock Assessment to estimate the total wood savings if every eligible home in the region installed a DHP (see Table 4).[[9]](#footnote-9) For example, in Heating Zone 1, there are 407,986 homes with electric resistance zonal heating that would be applicable for this example DHP program. If every eligible home in Heating Zone 1 installed a DHP, each home (on average) would save around 600 kWh-equivalent of wood (in terms of usable energy delivered to the conditioned space). This equals a total of 246,400 MWh equivalent of wood savings across the Heating Zone 1 as a result of reduced supplemental wood use.

Table 4. Candidates for DHP Installation and Total Potential Wood Savings (Energy Delivered to the Conditioned Space)

|  |  |  |
| --- | --- | --- |
| Heating Zone | Number of zonal electric homes | Wood savings, energy delivered to space |
| Each home (kWh) | Region total (MWh) |
| 1 | 407,986 |  604 | 246,400 |
| 2 | 111,150 |  204 |  22,700 |
| 3 |  34,559 | 1690 |  58,400 |

Data on types of heating appliances used throughout the region collected by the 2012 Residential Building Stock Assessment was combined with estimates of average appliance efficiency and fuel energy content to inform estimates of potential wood savings (in terms of cords of wood and tons of pellets) resulting from the installation of DHPs. For this savings estimate, the RTF used the following assumptions:

* The average cord-wood appliance is 50 percent efficient with an average energy content of 6070 kWh (20.7 Mbtu) per cord of wood[[10]](#footnote-10)
* The average pellet stove is 85 percent efficient with an average energy content of 3770 kWh (13.0 Mbtu) per ton of pellets [[11]](#footnote-11)

 Table 5 Total Potential Wood Savings (Cords of Wood and Tons of Pellets)

|  |  |  |  |
| --- | --- | --- | --- |
| Heating Zone | Share of total wood-fuel energy | Savings, energy delivered to space (MWh) | Quantity saved |
| Cord wood | Pellets | Cord wood | Pellets | Cords of wood | Tons of pellets |
| 1 | 85.5% | 14.5% | 210,709 | 35,691 |  69,426  | 11,138  |
| 2 | 87.8% | 12.2% |  19,931 |  2,769 |  6,567  |  864  |
| 3 | 99.6% | 0.4% |  58,147 |  253 |  19,159  |  79  |

The COBRA model, used for the dispersion modeling described in the next step of quantification, requires inputs in terms of percentage or absolute decrease in pollutants annually. The RTF calculated this percentage decrease based on potential tons of wood combustion reduction (from Table 5) and data on wood burning appliances in the Pacific Northwest provided by the EPA Residential Wood Combustion report.[[12]](#footnote-12)

The total reduction in emission from avoided supplemental wood heat is thus calculated as a product of (1) cords of wood and tons of pellets avoided and (2) a weighted average mix of emission factors from existing appliances in the region. In this calculation, the RTF assumed that the reduction of wood combustion due to the installation of a DHP was in the same proportion as the existing wood appliance distribution. The results are presented in Table 6 and used in the next step of the quantification process.

Table 6. Scenario Inputs: Wood Smoke Pollutant Reduced from Complete Electric Resistance Zonal to DHP Conversion

|  |  |  |
| --- | --- | --- |
| Pollutant | Tons reduced by climate zone | % Reduction by climate zone |
| HZ1 | HZ2 | HZ3 | HZ1 | HZ2 | HZ3 |
| Ammonia | 52 | 5 | 12 | 3.64% | 0.34% | 2.7% |
| Volatile Organic Compounds | 1,294 | 119 | 308 | 4.48% | 0.41% | 2.8% |
| Primary PM2.5 | 997 | 92 | 238 | 4.07% | 0.38% | 2.8% |
| Sulfur Dioxide | 17 | 2 | 4 | 4.16% | 0.38% | 3.0% |
| Nitrogen Oxides | 107 | 10 | 25 | 4.03% | 0.37% | 3.0% |

### Net Emissions Effects

By reducing electric resistance zonal space heating energy use, a DHP program may also reduce emissions from electric generation plants. Potential emissions reductions at electric generating plants would be diminished somewhat in DHP programs when DHP heat is displacing supplemental wood heat. These net changes in emissions at generating plans were not considered in the DHP example in this study.

### RTF Conclusions and Recommendations for Step 1: Quantify Emissions Changes

Based on this analysis, the RTF believes that wood smoke reductions can be directly attributed to specific efficiency programs and that those reductions can be quantified. The DHP example demonstrates that methods based on pre- and post-billing data and basic site characteristics can be transparent and sound. Although, since billing data are highly variable, there are limits to the precision of such methods. In the case of DHPs, the Heating Zone 1 sample size is large enough that the standard error for the zone as a whole is low. The standard errors in Heating Zones 2 and 3 are moderate. To strengthen the causal link, control groups should be considered for future studies. Additionally, since estimates for wood use and appliance mix came from state survey data, the RTF recommends periodic updates to this survey to ensure the reliable quantification of changes in wood smoke resulting from efficiency programs.

The RTF cautions against generalizing the results of the DHP analysis to other energy efficiency measures and recommends that more research is needed on a measure-by-measure basis to determine the extent weatherization and other efficiency measures produce changes to supplemental wood heat.

Additionally, as demonstrated further in Step 2 (Section 3.2 below), health effects are proportional to the size of the affected population. Therefore, per measure wood savings estimates may need to be determined through dedicated studies in major population centers.

## Step 2: Dispersion Modeling

The next step to quantify the potential health effect from supplemental wood heat reductions is to estimate the change in amount of PM2.5 created by supplemental wood heat after DHP installation and to model geographic dispersion of those particles. For this, EPA uses computation dispersion models that use mathematical formulations and inputs of average local weather patterns, geography, and other physical attributes to model the creation, spread and dissipation of pollutants. This step is important because it recognizes that emission reductions at the household-level may be less or more than at a regional level (the levels at which RTF measures are evaluated) depending on how those emissions are dispersed in the atmosphere.

The RTF used COBRA[[13]](#footnote-13) for analysis. The model demonstrated that reductions in residential wood smoke emissions had bigger health impacts in areas of higher population density, which were not the same areas where the largest reductions occurred. This is an important finding because it means that energy efficiency measures at the local level can have a much larger beneficial effect on the region or can benefit other regions where the efficiency measure was not implemented.

The RTF used the emission reduction values from Step 1 (presented in Table 6) as inputs to the COBRA model. Figure 1 and Figure 2 below are COBRA output maps. Figure 1 depicts the geographic distribution of base-level PM2.5 concentration (prior to program intervention). The darker color in this map signifies higher concentrations in the base-level PM2.5. Figure 2 shows the estimated reductions in PM2.5 resulting from the DHP program. The darker color in this case represents a larger change in PM2.5 concentration.

Figure 1 Base Levels of PM2.5 Concentration (micro grams/ cu. meter)



Figure 2 Post-Dispersion Reduction (Change) in PM2.5 Concentration (micro grams/ cu. meter)



Although region wide precision of results from COBRA are comparable to more sophisticated tools, EPA recommends COBRA as a screening tool due to limited validation studies of the S-R Matrix models.[[14]](#footnote-14) State-of-the-art dispersion models (e.g. CALPUFF, AERMOD, and CMAQ) use a more detailed approach to model atmospheric chemistry. These models give results with improved precision at the county level, both in terms of concentration of PM2.5 and the mass of PM2.5 that remains in the county versus that dispersed across county lines. Given that total health benefits from a fixed PM2.5 decrease is proportional to the population of a county and that efficiency programs are rarely adopted uniformly across the region, the RTF notes that a more precise model would enable better quantification at this step. Application of these state-of-the-art models would cost approximately $50,000 to $100,000. Although this cost would increase based on the number of modeled scenarios, the majority of the cost would be for construction of a base model.

### RTF Conclusions and Recommendations for Step 2: Dispersion Modeling

Dispersion modeling is a well established science; software packages that estimate pollutant dispersion with varying level of precision and detail are available. The EPA collects detailed data that can be used to calibrate and validate a list of approved computational dispersion models. EPA also regularly collects and publishes detailed data on pollutant concentration levels on a county by county basis.

The RTF conducted the dispersion modeling in this report using COBRA, which provides sufficient precision at the regional level, but EPA recommends limiting COBRA’s use to screening level studies only. Since the total health benefit from a fixed reduction in PM2.5 is proportional to the population of a county and efficiency programs are not uniformly adopted across the region, the RTF recommends first exploring the potential use of a higher precision dispersion model to better inform the local impacts from efficiency program delivery before attempting to quantify the potential health effects for a specific measure.

## Step 3: Estimate Health Effects

To estimate the health effect associated with a change in air quality, COBRA uses health impact relationships that have been used by the EPA’s Office of Air Quality Planning and Standards for Regulatory Impact Assessments. In evaluating health impacts of air pollution, the EPA relies on the synthesis of the clinical, toxicological, and epidemiological evidence regarding exposure to PM2.5 and other pollutants described in EPA’s 2009 *Integrated Science Assessment for Particulate Matter*.[[15]](#footnote-15)

The RTF does not have the expertise or resources needed to independently evaluate the conclusions of the Integrated Science Assessment. Since few entities have such resources, the EPA defined detailed processes for convening expert panels to assess scientific evidence and for soliciting peer review. This process is described in *Estimate of Premature Deaths Associated with Fine Particle Pollution (PM2.5) in California Using a U.S. EPA Methodology*.[[16]](#footnote-16) Additionally, details on the elicitation of the expert panel are provided in *Methodology for Estimating Premature Deaths Associated with Long-term Exposure to Fine Airborne Particulate Matter in California*.[[17]](#footnote-17) Based on the strength and openness of this scientific process, the RTF recommends accepting the Integrated Science Assessment conclusions.

### Results

Table 7 shows COBRA’s estimates of the health effects associated with a one year reduction in supplemental wood heat resulting from DHP installation in all eligible homes. The table expresses results in terms of total number of avoided cases of each health outcome. For example, region wide adoption of DHP (in program eligible homes as described above) would result in 12.46 to 28.23 avoided adult deaths.

Table 7 Expected Health Effects

|  |  |
| --- | --- |
| Health Outcome | Avoided Cases |
| Adult Mortality (low) | 12.46 |
| Adult Mortality (high) | 28.23 |
| Infant Mortality | 0.03 |
| Non-fatal Heart Attacks (low) | 1.30 |
| Non-fatal Heart Attacks (high) | 12.03 |
| Resp. Hosp. Adm. | 2.63 |
| CVD Hosp. Adm. | 3.09 |
| Acute Bronchitis | 21.80 |
| Upper Res. Symptoms | 396.41 |
| Lower Res. Symptoms | 277.74 |
| Asthma ER Visits | 5.59 |
| MRAD | 11,257.00 |
| Work Loss Days | 1,901.14 |
| Asthma Exacerbations | 415.50 |

Estimates in the table are based on population projections for 2017 estimated changes in ambient PM2.5, and the epidemiological links estimated in the primary studies cited by the Integrated Science Assessment.

Health effects related to PM2.5 have been estimated in multiple primary studies. Individual estimates have relatively wide error bands (confidence bounds of plus or minus 50 percent are common), but the collective evidence is stronger than any individual study since multiple studies yield similar results. Estimates vary due to differences in study populations, model specification, and statistical error. EPA’s Integrated Science Assessment provides a graphical representation of different estimates of the relationship between long-term PM2.5 and premature mortality.[[18]](#footnote-18) For these reasons, COBRA provides high and low estimates of the mortality effect based on the results of two major epidemiological studies—rather than relying on a single study. These two studies are summarized below to provide a sense of the scale of research EPA used to quantify the relationship between PM2.5 and mortality:

* **High-end mortality estimate (Lepeule Study).** This study is based on the Harvard Six Cities Study Cohort, a data set that tracks approximately 8,000 participants living in six Eastern and Midwestern US cities starting from 1974. During the study period, ambient PM2.5 observations ranged from 11 to 24 μg/m3.[[19]](#footnote-19)
* **Low-end mortality estimate (Krewski Study).** This study is based on the American Cancer Society cohort, a data set that tracks around 500,000 participants in 116 US cities starting from 1982. The ambient PM2.5 observations ranged from 5.8 to 22.2 μg/m3.[[20]](#footnote-20)

The COBRA User’s Manual[[21]](#footnote-21) describes all of the studies used in the calculations behind Table 7, including the mortality studies just referenced. For a better understanding of the calculations behind this model, Appendix C provides a detailed example to explain how these study results should be interpreted.

### RTF Conclusions and Recommendations about Step 3: Estimating Health Effects

Health effects can be difficult to study quantitatively and public health organizations have devoted extensive resources to the scientific effort. The RTF recommends accepting the EPA’s Integrated Science Assessment conclusions with respect to quantification of the epidemiological link. Most studies referenced by the Integrated Science Assessment are statistically significant and independent of other studies. Although the estimates from these individual studies generally have wide error bands, they collectively yield reasonable estimates.

The Integrated Science Assessment indicates that there is still uncertainty around the exact form of the concentration-response mechanism. For example, a threshold effect is possible (but not necessarily expected). Pollutants, however, are not distributed uniformly so population-average health effects have limited sensitivity to this sort of structural detail.

## Step 4: Monetize Health Effects

EPA is currently using a suite of economic values for avoiding various health risks, informed by published estimates of the costs of treating the illness (this can include both direct medical costs and the costs of lost productivity).[[22]](#footnote-22) COBRA uses these values to calculate the monetary value of health impacts. Table 8 presents the predicted valuation results applied by COBRA per EPA recommendation.

Table 8 EPA Approved Mortality and Morbidity Benefit

|  |  |  |
| --- | --- | --- |
| **Health Incident Avoided** | **Incidence Classification** | **Economic Value (2010$)** |
| **Time-varying costsa** |
| Adult Mortalityb (3% discount rate) | Mortality | $8,434,924 |
| Adult Mortalityb (7% discount rate) | Mortality | $7,512,853 |
| Non-Fatal Heart Attacks (3% discount rate) | Morbidity | $33,259 - $263,795 |
| Non-Fatal Heart Attacks (7% discount rate) | Morbidity | $31,446 - $253,247 |
| **Costs incurred in the year of exposure** |
| Infant Mortalityb | Mortality | $9,401,680 |
| Hospital Admissions (Respiratory, Cardiovascular-related) | Morbidity | $15,430 - $41,002 |
| Asthma Emergency Room Visits | Morbidity | $388 - $464 |
| Acute Bronchitis | Morbidity | $477 |
| Respiratory Symptoms (Upper, Lower) | Morbidity | $21 - $33 |
| Asthma Exacerbations (attacks, shortness of breath, and wheezing) | Morbidity | $57 |
| Minor Restricted Activity Days | Morbidity | $68 |
| Work Loss Days | Morbidity | $151 |

1. COBRA assumes that most health effects and their economic values occur in the year of analysis. However, since all avoided cases of adult mortality do not to occur in the year of analysis, COBRA uses a discount rate to calculate the value of all avoided cases of adult mortality in present terms. In addition, while avoided cases of non-fatal heart attacks are expected to occur in the year of analysis, the costs associated with this health effect would occur over multiple years. Thus, while a COBRA emissions scenario may result in a certain number of cases of non-fatal heart attacks in 2017, all economic benefits associated with these emissions changes would not accrue in that same year. The values presented are discounted to present terms.
2. Following EPA (2012),[[23]](#footnote-23) COBRA assumes that some of the incidences of premature adult mortality related to PM2.5 exposures occur in a distributed fashion over the 20 years following exposure. This lag adjustment does not apply to infant mortality, because Woodruff et al. (1997) estimate the number of infant deaths occurring in the same year as the emissions change.[[24]](#footnote-24)

### Value of Statistical Life

The overwhelming majority, more than 98 percent, of the monetized health benefits come from avoided premature mortality. The EPA has conducted extensive research on mortality and defines the monetized health benefit in terms of Value of Statistical Life (VSL). The VSL estimates the society’s willingness to pay for a reduction in micro risk (defined in terms of dollars per micro risk). For example, if 10,000 individuals are each willing to pay $500 for a reduction in risk of 1/10,000, then the value of saving one statistical life equals $500 times 10,000—or $5 million. Note, this does not mean that any single identifiable life is valued at this amount. Rather, the aggregate value of reducing a collection of small individual risks is, in this case, worth $5 million.

Economists employ two methods to estimate VSL: (1) revealed preference method and (2) stated preference method. The revealed preference method analyses the amount of incremental payment a worker receives for incremental increase in fatality risk on the job. After statistically controlling for factors such as education, and occupation, this method attempts to answer the question: how much compensation do workers receive for bearing extra risk? The stated preference method establishes a VSL by asking people hypothetical questions on how much they are willing to pay to reduce a very small risk—called a micro risk—to fatality.

EPA uses 26 studies as the basis for its recommendation for VSL (see Table 9). EPA conducted a meta-analysis of these studies to obtain a central estimate of $7.4 million, with a standard deviation of $4.7 million (in 2008 dollars), which it recommends for all its analyses.[[25]](#footnote-25)

Table 9 EPA Guidelines Summary VSL

|  |  |  |
| --- | --- | --- |
| Study | Method | Value of Statistical Life (million dollars) |
| Kniesner and Leeth (1991 - US) | Revealed Preference | $0.85  |
| Smith and Gilbert (1984) | Revealed Preference | $0.97  |
| Dillingham (1985) | Revealed Preference | $1.34  |
| Butler (1983) | Revealed Preference | $1.58  |
| Miller and Guria (1991) | Stated Preference | $1.82  |
| Moore and Viscusi (1988) | Revealed Preference | $3.64  |
| Viscusi, Magat, and Huber (1991) | Stated Preference | $4.01  |
| Marin and Psacharopolous (1982) | Revealed Preference | $4.13  |
| Gegax et al. (1985) | Stated Preference | $4.86  |
| Kniesner and Leeth (1991 - Australia) | Revealed Preference | $4.86  |
| Gerking, de Haan and Schulze (1988) | Stated Preference | $4.98  |
| Cousineau, Lecriox, and Girard (1988) | Revealed Preference | $5.34  |
| Jones - Lee (1989) | Stated Preference | $5.59  |
| Dillingham (1985) | Revealed Preference | $5.71  |
| Viscusi (1978) | Revealed Preference | $6.07  |
| R.K. Smith (1974) | Revealed Preference | $6.80  |
| V.K. Smith (1983) | Revealed Preference | $6.92  |
| Olson (1981) | Revealed Preference | $7.65  |
| Viscusi (1981) | Revealed Preference | $9.60  |
| R.S. Smith (1974) | Revealed Preference | $10.57  |
| Moore and Viscusi (1988) | Revealed Preference | $10.69  |
| Kniesner and Leeth (1991 - Japan) | Revealed Preference | $11.18  |
| Herzog and Schlottman (1987) | Revealed Preference | $13.36  |
| Leigh and Folsom (1984) | Revealed Preference | $14.21  |
| Leigh (1987) | Revealed Preference | $15.31  |
| Garen (1988) | Revealed Preference | $19.80  |

### Alternative VSL Estimates and VSL Adjustment Considerations

Other US government agencies use their own estimate for VSL, with values ranging between $1 and $10 million.[[26]](#footnote-26)

The RTF investigated the influence of population age on VSL estimates.[[27]](#footnote-27) Although all federal agencies employ a uniform VSL number across all age groups, a study by Aldy and Viscusi argues that VSL vary by age.[[28]](#footnote-28) The study states that VSL from revealed preference studies increases with age, peaks in mid-life, and subsequently declines. According to the study, the assumption that a 60 year old has a lower VSL than a 20 year old is false because a 60 year old is likely to have lower tolerance for mortality risk and higher savings. The Science Advisory Board in a 2007 memo to the EPA recommended that: *“Although the literature on the relationship between age and the VSL is growing, the Committee does not believe that it is sufficiently robust to allow the Agency to use a VSL that varies with age*.”[[29]](#footnote-29) Additionally, varying VSL estimates based on age leads to questions on the fairness of policy. Therefore, federal agencies generally apply the same mean VSL estimates across all individuals potentially affected by their regulations—regardless of age, income, or other characteristics.

### RTF Conclusions and Recommendations on Step 4: Monetize Health Benefits

Attempting to estimate VSL is expensive and complicated. Although economists have settled on willingness to pay methods through revealed and stated preference studies as an established method to estimate VSL, the science behind the methods of estimation continues to evolve and refine. Even though different studies on VSL have been conducted at various points of time, with differing methodology, and dataset, they all produce VSL estimates within an order of magnitude ($1 to $12 Million, see Table 9). That such differing studies produce VSL within one order of magnitude is a *significant* finding.[[30]](#footnote-30) It is also important to note that the range and magnitude of VSL make it a significant contributor to the magnitude and variance of health effects from changes in wood smoke.

Since determining an RTF specific VSL would be expensive and beyond the group’s expertise, the RTF recommends using the existing data. The selection of a VSL is a policy choice, although the RTF cautions against using a point estimate alone for analysis. Rather, the RTF recommends using a range. The RTF would be an appropriate body to conduct sensitivity analyses on the range and interpret how those affect the cost-effectiveness of a measure.

# Study Results

The RTF followed the four step process described in the previous section to calculate the monetary benefits of reduced wood use that is directly attributable to a region wide DHP program. The RTF used both the high and low end of the quantification of health impact (Section 3.3) and monetization of health benefit (Section 3.4) ranges in this analysis. The results, as shown in Table 10 reveal health benefits ranging from $95 million to $241 million from reduced supplemental wood heat resulting from the conversation from a electric resistance zonal heating system to a DHP. Such an efficiency program is expected to save the region 1,900 GWh of electric energy. In terms of monetary benefit per kWh electric energy saved, this value ranges from $0.05 to $0.13 per kWh electric energy saved.

Table 10 Derivation of $ Benefit per kWh Saved by the DHP Program

|  |  |  |
| --- | --- | --- |
| Total Health Benefits (2010$)a | Regional Total Savings Potential (GWh) | $/ kWh Saved |
| Low | $94,970,500 | 1,900 | $0.05 |
| High | $240,873,900 | $0.13 |

\* The sum of low and high end mortality and morbidity benefits in Table 19 and Table 20 in Appendix D provide the high and low end of total health benefits.

Appendix D presents the details of this calculation. This calculation is approximate and meant to provide an idea of the range of benefits from reduced wood smoke from an energy efficiency zonal heating system to DHP conversion program.

# Conclusions and Recommendations

Using a DHP program example, the RTF walked through a four step analysis to determine the potential to directly link changes in wood smoke emissions to a specific energy efficiency measure and use those changes to quantify health effects. Based on this analysis, the RTF concludes that wood smoke reductions, and the resulting health effects, can be directly attributed to certain efficiency programs and that those reductions can be quantified. The range of these estimates has wide error bounds, but even at the low end the impacts of cost effectiveness would be significant for some energy efficiency measures.

Of the four steps, the RTF is best positioned to assess the quantification of emissions change from efficiency programs. The development of the DHP estimate provides a good example of the ability to make this direct link and quantification using robust pre- and post-billing data. The RTF recommends assessing the data requirements and analysis needed to quantify emissions changes resulting from weatherization and other energy efficiency measures that have interactive effects with the heating system.

For the last three steps—dispersion modeling, estimating health effects, and monetizing health benefits—the RTF is reliant on existing data and expertise in the scientific community. Dispersion modeling is a well established science based on EPA collected and published data that is routinely updated. While the COBRA model used for this analysis is recommended for screening purposes only, the RTF recognizes that more precise models are available to support more robust county level analysis.

The quantification and monetization of the health effects from changes in wood emissions bring the greatest uncertainty. These steps are difficult to quantify. Years of expert research in these fields yield results that, when taken collectively, provide a reasonably reliable estimate to work from. Unlike the first two steps, the RTF has limited ability to reduce the uncertainty around these numbers. Therefore, the RTF recommends leveraging this research to inform its work—being mindful of the analytical basis and uncertainty—and working with the ranges. The RTF is well positioned to support the interpretation of these ranges and the potential impacts to a specific energy efficiency measures.

# Appendix A. Estimating Wood Heat Reduction from Ductless Heat Pump Installations

This appendix presents the RTF’s evidence for DHP-related wood heat savings in greater detail. It also develops wood savings estimates from this evidence in order to convey the extent to which these savings may be realistically quantified using existing data.

The calculations below are very similar to those used in the RTF’s DHP measure workbook. The differences are very minor, and are only due to the fact that this paper seeks to connect estimates to the data in the simplest and clearest manner possible, whereas RTF savings estimates need to satisfy additional requirements (especially consistency with other measures).

As a reminder, the central data source behind these estimates comes from the impact evaluation for NEEA’s DHP pilot program.[[31]](#footnote-31) The pilot program installed almost 3,400 ductless heat pumps in the Pacific Northwest, and collected pre- and post-DHP billing data for all participants. The impact evaluation was based on billing data and sub-metered end-use data collected for about 100 sites.

### Basic Evidence of Emissions Changes

Table 11 presents heating energy averages, pre- and post-DHP, separately for homes with and without wood heat.

Table 11. Pre-DHP and post-DHP heating energy averages based on billing data

|  |  |  |
| --- | --- | --- |
|  | **Homes without wood heata** | **Homes with wood heat** |
| **Heating zone** | **Pre-DHP, kWh** | **Post-DHP, kWh** | **Pre minus post, kWhb****(SE)c** | **Pre-DHP, kWh** | **Post-DHP, kWh** | **Pre minus post, kWh2****(SE)3** |
| **1** | 7,603 | 4,810 | 2,793 (93) | 6,112 | 5,159 |  952 (140) |
| **2** | 10,973 | 9,025 | 1,948 (384) | 7,263 | 7,334 |  -71 (435) |
| **3** | 11,326 | 9,441 | 1,885 (487) | 8,553 | 9,175 | -622 (460) |
| a This wood heat designation is based on a telephone survey. In subsequent site visits, researchers discovered that the survey failed to capture a significant amount of wood heat.b  Since some homes designated as having no wood heat actually do have some wood heat (see previous note), savings among homes that truly have no wood heat should be greater than what is indicated in the table. As a result, the true savings gap between homes with and without wood heat should be even greater.c The table shows approximate standard error (SE) for each of the kWh savings values. At the 95% confidence level, an estimate’s error band is plus/minus about two standard errors. |

The preliminary savings estimates in the table (columns 3 and 6) provide wood savings evidence of wood savings in terms of raw averages. The table shows that the electric savings due to ductless heat pumps is much lower in homes with wood heat than in homes without wood heat. This is true in all climate zones, and cannot be accounted for by statistical error.[[32]](#footnote-32)

The first column of Table 15 in Appendix B shows that homes with high levels of wood heat tend to use 20% to 40% less electric heating energy, but the savings figures in Table 13 differ by much more than 20-40%. The impact evaluation concluded that occupants must burn less wood after installing a DHP. This assertion is well supported by the data.[[33]](#footnote-33)

### Wood Savings Estimates

The calculations that follow are complicated by the need to normalize estimates to Residential Building Stock Assessment building averages and long-term weather; some of these complications are commonplace among current RTF energy estimates. In any event, the estimates themselves ultimately rely on the basic evidence identified in the billing analysis and illustrated in Table 11.

To obtain results that reflect the residential building stock in the Northwest, the RTF uses a calibrated engineering model to estimate residential energy consumption and savings. For DHPs, electric and wood savings are calculated separately for each heating zone. The procedure is based on these elements:

* Estimates of differences in electric heating energy intensities (kWh/sq. ft.) between homes with and without wood heat. Heating energy intensities are based on billing analysis results and home sizes (about 2300 participants with wood heat and 1100 without).
* Residential Building Stock Assessment-based estimates of the fraction of homes in the region that have wood heat (about 1400 homes in the Residential Building Stock Assessment).
* Estimates of total heat load that reflect the building characteristics in the Residential Building Stock Assessment. These are based on an engineering model that is calibrated using a subset of the pilot study for which researchers collected detailed audit and sub-meter. The sub-meter study included 78 sites with negligible wood heat.

The values used in RTF wood heat calculations are summarized in Table 12.

Table 12 Inputs to Wood Savings Estimates

|  |  |  |
| --- | --- | --- |
| **Heating zone** | **Electric heating energy intensity****(kWh/ft2)** | **Percent of DHP-eligible homes that have wood heat** |
| **Pre-DHP****homes without wood heat** | **Pre-DHP****homes with** **wood heat** | **Post-DHP****homes without wood heat** | **Post-DHP****homes with** **wood heat** |
| **1** | 5.02 | 3.66 | 3.18 | 3.08 | 28% |
| **2** | 6.84 | 3.55 | 5.62 | 3.58 | 20% |
| **3** | 5.87 | 3.73 | 4.89 | 4.00 | 70% |

The values in the table can be used to estimate the fraction of heating load that is met with wood heat in the pre- and post-DHP cases.

As an example, consider pre-DHP homes in heating zone 1. Within this group, the average electric heating energy intensities of homes *without* wood heat is 5.02 kWh/ft2, and the average for homes *with* wood heat is 3.66 kWh/ft2. Based on this, zone 1 homes that have wood heat apparently meet about 3.66/6.02 = 73% of their heat load with electricity, and they meet the remaining 27% with wood. Similar calculations suggest that these homes meet 97% of their heating loads with electricity and 3% with wood after installing DHPs.

The next step is to use these heating shares to estimate the amount of heating energy that is contributed by wood-burning devices.

These calculations rely on a clear distinction between the amount of thermal energy used to heat a house (the *heat load*) and the amount of electric energy used to meet the heat load. These are not always the same, even in homes that are exclusively heated by electric appliances.[[34]](#footnote-34)

The RTF’s current DHP measures apply to homes whose primary electric heat source is zonal-electric (baseboard heaters). Zonal electric heat is 100% efficient – the amount of thermal energy delivered to the house equals the amount of electric energy consumed by the baseboard heaters – so in the pre-DHP case, the heat load is the same as the electric heating energy.

In the post-DHP case, the heat load and the electric energy needed to meet the load are not necessarily the same because occupants sometimes increase their thermostat settings when they obtain an efficient heat source such as a DHP (this behavior is called “comfort take-back”). The RTF’s energy model calibration focuses on the energy *consumed* by heating appliances, not the thermal energy the appliances *produce.* Because of this, the model only produces calibrated heat load estimates in the case of homes with zonal electric heat (see previous paragraph). For other heat sources, the calibration adjustments may reflect comfort take-back, or uncertain model inputs (such as a heat pump’s effective coefficient of performance), or both.

Table 13 shows three types of estimates. The first is the pre-DHP heat load, which is the same as the electric energy used to heat a zonal-electric home with no supplemental heat; if there is no comfort take-back, this is the same as heat load in the post-DHP case. The second is a rough estimate of the post-DHP heat load that assumes the relevant RTF calibration adjustments are entirely due to comfort take-back. The third is the estimated electricity used to heat the home in the post-DHP case; this is only provided to underscore the distinction between heat load and energy used to meet load.

Table 13 Energy estimates from based on calibrated engineering model

|  |  |  |  |
| --- | --- | --- | --- |
| **Heating zone** | **Heat load,** **zonal-electric****(kWh)** | **Heat load (high)a** **DHP homes** **(kWh)** | **Heating energyb** **DHP homes****(kWh)** |
| **1** | 9,068 | 10,434 | 5,757 |
| **2** | 10,987 | 12,644 | 7,680 |
| **3** | 14,528 | 16,760 | 11,307 |
| a As explained above, the RTF’s current methods do not yield a calibrated estimate of the average post-DHP heat load. The first two columns in the table bracket the range likely values. The true value depends on the role of comfort take-back in the RTF’s model calibration.b Heating energy refers to the amount of electric energy needed to heat a home that has no supplemental fuels. This is not the same as the heat load (see above).  |

The calculations following Table 12 estimated that zone 1 homes with wood heat meet about 27% of their heating loads with wood prior to installing DHPs. Based on Table 13 this corresponds to 0.27\*9,086 = 2,448 kWh delivered into the conditioned space. Assuming the average wood-burning appliance efficiency is around 50%, this says that the average energy content of the wood burned by these homes is about 4,900 kWh.[[35]](#footnote-35)

The same calculation estimated that 3% of the load is met with wood in the post-DHP case. Depending on comfort take-back, this corresponds to between 272 and 313 kWh delivered into the conditioned space. We therefore estimate that, on average, when a DHP is installed in a heating zone 1 home that has wood heat, the wood saved is an amount that would deliver between 2135 and 2176 kWh of thermal energy into the conditioned space. Assuming 50% wood-burning efficiency and 6000 kWh per cord, that’s little more than 2/3 of a cord.

Since 28% of DHP-eligible homes in zone 1 have wood heat, we estimate the overall average wood savings as 598 - 609 kWh (delivered to the conditioned space.

The following table summarizes the wood savings calculations for all three zones.

Table16 Estimated wood savings due to ductless heat pumps

|  |  |  |
| --- | --- | --- |
|  | **Percent of load met with wood****(homes with wood heat)** | **Average wood savings per DHP****(energy delivered to space, kWh)a** |
| **Heating zone** | **Pre-DHP** | **Post-DHP** | **Homes with wood heat** | **Average across all homes** |
| **1** | 27% | 3% | 2135 - 2176 | 598 - 609 |
| **2** | 48% | 36% |  722 - 1318 | 144 - 264 |
| **3** | 36% | 18% | 2213 - 2615 | 1549 - 1831  |
| a The range of saving values reflects uncertainty about the magnitude of comfort take-back. Low-end savings values correspond to greater comfort take-back, and high-end savings values correspond to no comfort take-back.  |

In Table 14, the range of values in the wood savings estimates reflects the likely range of comfort take-back effects. Uncertainty due to other factors, such as statistical error in estimates of heating energy intensity or in the RTF’s model calibration, is not reflected in the ranges.

The main logical weakness in these estimates is that the DHP study did not use a control group, so it is possible that some external phenomenon may have driven a region-wide reduction in wood burning that happened to coincide with the DHP pilot program. (For example, maybe there happened to be more burn bans in the period after the program than in the period before the program). This is mentioned for completeness, not to suggest that it represents a significant threat to the study’s main findings. Few studies are able to eliminate all possible logical gaps.

# Appendix B. Wood heat and Weatherization

This appendix describes how the RTF uses Residential Building Stock Assessment data to estimate the electric energy displaced by wood fuels. The discussion shows that *these estimates* *do not directly address our present concern*, and it highlights the fundamental question that must be answered in order to quantify wood heat savings due to weatherization measures. The RTF’s opinion is that this question can be answered with reasonable precision through practical means.

The RTF uses the Residential Building Stock Assessment to estimate how wood heat affects electric energy savings due to non-DHP measures. The Residential Building Stock Assessment includes data from site audits, utility bills, and occupant interviews. The interview responses describe “wood” fuel consumption in terms of cords of wood, tons of pellets, and gallons of propane. The RTF uses the billing- and wood-fuel data to estimate the differences in electric heating energy that are associated with different levels of wood fuel consumption. This analysis only looks at electrically heated single-family homes (homes with a gas furnace, for example, are excluded). Table 15 summarizes the results of this analysis for heating zone 1 (results are similar in zones 2 and 3).

Table 15 Wood Heat and Electric Heating Energy in Heating Zone 1

|  |  |  |  |
| --- | --- | --- | --- |
|  | **Electric heating energy difference (affected homes)** | **Percent of Zone 1 homes affected** | **Net electric heating energy difference** |
| **Wood (kWh) 6K to 12K** | -20% | 30% | -6.2% |
| **Wood (kWh) Over 12K** | -39% | 11% | -4.3% |
| **Total**  |  |  | **-10.5%** |

To understand what the table says, consider the first row: On average, a home that consumes between 6,000 and 12,000 kWh-equivalent in wood fuels will use about 20% less electric heating energy than a similar home that uses no wood fuel;[[36]](#footnote-36) according to the Residential Building Stock Assessment, about 30% of the homes in heating zone 1 have wood heat in this range; the net effect is that is that zone-1 homes use about 0.20\*0.30 = 6.2% less, on average, because of the presence of wood heat.

We can use these results, together with Residential Building Stock Assessment data on wood-burning appliances, to estimate the average number of cords of wood that are burned in the region’s electrically heated homes.

However, a fundamental question remains: How does wood fuel consumption change when we install weatherization measures in homes that use wood heat. Different occupants will respond differently, so we can only hope to answer this question in terms of averages. For discussion, imagine a weatherization measure that reduced a home’s heat load by 15% and consider three possible scenarios:

1. Occupants like the aesthetic qualities of wood heat and do not change their wood consumption at all when their heating load changes.
2. Occupants use wood as a primary heating fuel, and their consumption changes in proportion to heating load.
3. Occupants use wood heat during the coldest part of the year when their other equipment cannot meet load. Post weatherization, the other equipment can meet the load at almost all times, so wood fuel consumption decreases dramatically.

Most program populations include representatives of each of these scenarios. Wood heat reductions due to weatherization must depend on the mix of participant types. This issue would need additional study before the RTF could reliably quantify wood heat savings do to weatherization and non-DHP heating equipment upgrades.

The estimates in the following table assume wood consumption changes, on average, in proportion to heating load (as in scenario 2 above). These estimates are very rough. The intention is only to provide order-of-magnitude reference points, not rigorous estimates.

Table 16 Wood savings based on 6th Plan estimates of achievable measure potential by 2029.

|  |  |  |
| --- | --- | --- |
| Measure | Total estimated energy savings (2029 achievable potential) | Derived wood savings |
|  **(MWa)** |  **(MWh)** | **(Cords)a** |
| Weatherization (all measures)  | 290 | 2,540,400 | 84,700 |
| Furnace to HP conversion | 100 | 8,760,000 | 28,860 |
| a Assumes 10% of load is met by wood heat in pre- and post-cases, 6070 kWh per cord, and 50% efficiency of wood burning device. Formula is Cords = (kWh)\*(0.10)\*(1/5700)\*(1/0.50). |

As noted above, these estimates are only order-of-magnitude approximations. The COBRA scenarios described in this document are based on wood savings due to ductless heat pumps; the figures in Table 16 are not used outside of this Appendix.

# Appendix C Detailed Example

This appendix examines critical steps in COBRA’s mortality calculations for a hypothetical policy objective. The goal is to make the calculation steps as concrete as possible to better understand (1) what the COBRA outputs mean, and (2) how one should interpret the epidemiological results. This development emphasizes clarity over precision—the calculations are not particularly precise, nor does COBRA claim great precision for isolated examples.

The policy objective is this:

*Promote ductless heat pumps in sufficient quantity to decrease residential wood smoke emissions in Clackamas County, Oregon, by 10% beginning in the year 2017.*

This scenario is entered into COBRA by first limiting our intervention scenario to Clackamas County, Oregon, then highlighting “RESIDENTIAL WOOD” in the scenario definition and specifying a 10% reduction in each of the five pollutants (PM2.5, SO2, NOX, NH3, and VOC).

The monetary results are summarized in Table 19. COBRA provides a range of values, $1.22M to $2.75M, for total health-effects. This valuation is for multiple years’ health impacts that are due to a single year (2017) of emissions change; since the change is persistent, this value recurs, with adjustments, annually once the change has occurred.

Table 17. Main contributors to health effect valuation

|  |  |  |  |
| --- | --- | --- | --- |
|  | **Valuation range****(all health effects)** | **Valuation range****(adult mortality)** | **Percent of valuation****total (all health effects)a** |
| Clackamas County | $0.40M - $0.91M  | $0.40M - $0.90M | 32.6% |
| Multnomah County | $0.50M - $1.14M | $0.49M - $1.12M | 40.7% |
| Other  | $0.31M - $0.70M | $0.31M - 0.70M | 25.3% |
| **Total** | **$1.22M - $2.75M**  | **$1.20M - $2.72M** | **98.6%** |
| a Values in the second column, divided by the total values in the last row of the first column. |

### Narrowing the Example

In Table 17, a single health outcome—adult mortality—accounts for over 98% of the total health-effects valuation. The adult mortality effect ranges in value from $1.20M to $2.72M. Furthermore, about 74% of the Pacific Northwest adult mortality effect is from Clackamas County and neighboring Multnomah County. This is because these are populous counties in locations that experience significant air quality improvements under the defined scenario.

COBRA provides a range of values for adult mortality effects (in Table 17, the range for Multnomah County is $0.49M - $1.12M). The lower limit of this range is based on the mortality-PM2.5 link as estimated by the Krewski study;[[37]](#footnote-37) the upper limit is based on the estimate of the Lepeule study.[[38]](#footnote-38) The only difference in the calculations behind the upper and lower limits is the different estimates of the epidemiological link. The two calculations use identical values for the change in ground-level pollutants and the value of a statistical life.

This appendix focuses on the *lower limit* of the *mortality effect* in *Multnomah County*. Calculations for the upper limit and for other counties would be nearly identical. Calculations related to other health effects may differ but mortality effects account for nearly all of the total valuation.

The Multnomah County figures in Table 17 are based on a 0.002 μg/m3 decrease in ambient PM2.5. This is the average ground-level decrease across the entire county, over the entire year. As described in Section 3.2, COBRA uses the source-receptor matrix to estimates PM2.5. Below, we take the 0.002 μg/m3 figure as given and focus on the epidemiology.

### The Epidemiological Link

Like many epidemiological studies, the Krewski study estimates effects by fitting a *Cox proportional hazard model*. This kind of model quantifies the way *hazard functions* change in response to changes in long-term PM2.5 exposure levels. The hazard function can be thought of as an individual’s mortality rate. Roughly, it gives the individual’s probability of dying between age and age , given that he or she has survived to age *n*.[[39]](#footnote-39) Different individuals have different hazard functions depending on sex, occupation, family history, exposure to pollutants, and other variables.

In the study, the researchers estimate that, on average, hazard functions decrease by about 0.6% with every 1 μg/m3 decrease in PM2.5 concentrations.[[40]](#footnote-40), [[41]](#footnote-41) The study does not tell us anything about the hazard function itself; it only tells us how adult mortality hazard rates change, on average, when we change our assumption about long-term PM2.5 exposure.

To see what the result means, imagine two demographically similar populations. The only systematic difference between them is that they live in areas with different PM2.5 concentrations: The second group’s ambient concentration averages 20 μg/m3 higher than that of the first group. In this case, the model tells us that because of this difference the second population’s average adult-mortality hazard rate will be about 20 × 0.006 higher. Thus, if 1.00% of 40-year-olds in group 1 die in a typical year, then about 1.012% of the 40-year-olds in group 2 are expected to die in a typical year.

In particular years, the two groups may experience the same number of deaths, or group 2 may have more deaths than group 1. The result only says that group 2 should experience deaths at a slightly faster rate on average. It follows that population 2 will eventually have a lower proportion of older people, and hence shorter life expectancy, than population 1. The model does not say whether the shorter life expectancy is due to lots people dying a little sooner or a few people dying a much sooner.

It is important to understand that the actual health benefit takes the form of a small change in the mortality rates of a large number of individuals, so a fractional number of expected deaths does not cause any great conceptual difficulty.

The ∆PM2.5 amount in our Multnomah County scenario is much smaller than in the example just described (0.002 μg/m3 versus 20 μg/m3), but the basic issues are the same.

### The Mortality Effect

The Krewski result says that changes in PM2.5 result in approximately proportional changes in mortality rates. The expected change in the number of deaths is approximately equal to 0.006 × ∆PM2.5(μg/m3) times the baseline number of deaths. The initiative in our example is expected to decrease PM2.5 by 0.002 μg/m3, so the mortality rate is expected to change by a factor of

To use this result, one must first estimate the baseline mortality rate in the population being studied.

The Centers for Disease Control (CDC) publishes annual death rates, by age, for each county in the United States. COBRA combines the CDC rates with demographic data to estimate baseline mortality rates for 2017.

For our example, COBRA projects that 455,205 individuals over age 30 will reside in Multnomah County in 2017 and 5,105 of these will die in that year.[[42]](#footnote-42) Combined with the previous calculation, this yields the following estimate for the expected change in the *county’s total number of adult deaths* associated with emission changes in 2017:[[43]](#footnote-43)

The projections can also be used to estimate the expected change in individual-level mortality risk.

### Individual Benefits and Valuation

As a result of the initiative’s impact on 2017 air quality, the average Multnomah County adult’s probability of dying prematurely will decrease by this amount:

Since 5,105/455,205 = 0.011, the average individual has about a 1.1% chance of dying in 2017. For this discussion, the exact baseline mortality figure less important than the *change* in mortality that is due to the initiative.

In round numbers, the average adult will have about a 1/100 chance of dying in 2017, and the initiative would decrease these odds by about 1/10,000,000. If, on average, adults in Multnomah place a value of $0.75 on this reduction in risk, then the VSL is $7,500,000.

Note that VSL research seeks to estimate the value that individuals place on individual-level benefits.[[44]](#footnote-44) This value is typically expressed in units of millions of dollars per life, but more natural units would be dollars per mortality micro-risk. Although there is no mathematical difference, the usual expression invites misinterpretation.

A $7,500,000 VSL figure would yield the following total value for the Multnomah County adult mortality benefit due to air quality changes in 2017:

Table 18 shows COBRA’s estimated adult mortality changes for Multnomah County under the initiative. The table shows an expected low-end mortality change of 0.059 units (deaths), which agrees with the calculations above. It also shows a $0.49m valuation for this benefit, which is close o the $0.44m figure just calculated. (COBRA’s uses a different VSL figure and the final values account for monetary discounting of effects that are due to 2017 emission changes but may occur several year later.)

Table 18. Mortality Estimates and Valuation.

|  |  |  |
| --- | --- | --- |
|  | **Range of expected change****(adult mortality)** | **Range of values for change** **(adult mortality)** |
| Multnomah County | 0.059 - 0.133  |  $0.49M - $1.12M |

As described COBRA estimates mortality changes that are due to changes in the PM2.5 concentration *for a single year, 2017*. Since ductless heat pumps last for several year, the $0.49m mortality benefit recurs *each year after the long-term health effects have had time to materialize* (the exact figure would change from one year to the next because of evolving baseline assumptions and monetary discounting).

# Appendix D Calculation Details of Total Health Benefit from DHP Conversion Program

This appendix presents detailed calculations behind the derivation of health benefits from reduced wood smoke by combining all the quantification and monetization steps presented in this report.

Table 19 present the total health benefits from morbidity health incidences avoided. The total health benefit is the product of total morbidity incidences presented in Table 9 and the EPA approved health benefit per incident Table 10.

Table 19 Total Health Benefits from Morbidity Incidents (2010$)

|  |  |  |  |
| --- | --- | --- | --- |
| Health Incident Avoided | Benefits (2010$)a | Cases | Economic Value (2010$, 7% discount rate) |
| Non-fatal Heart Attacks (low) | $117,595  |  1.30  | $152,579 |
| Non-fatal Heart Attacks (high) | $117,593  |  12.03  | $1,414,524 |
| Resp. Hosp. Adm. | $26,087  |  2.63  | $68,622 |
| CVD Hosp. Adm. | $24,098  |  3.09  | $74,400 |
| Acute Bronchitis | $477  |  21.80  | $10,399.55 |
| Upper Res. Symptoms | $27  |  396.41  | $10,706 |
| Lower Res. Symptoms | $27  |  277.74  | $7,498 |
| Asthma ER Visits | $426  |  5.59  | $2,382 |
| MRAD | $42  |  11,257.00  | $474,802 |
| Work Loss Days | $151  |  1,901.14  | $287,072 |
| Asthma Exacerbations | $57  |  415.50  | $23,683 |
| *Total Morbidity Benefits (Low)* |  |  | *$1,112,145* |
| *Total Morbidity Benefits (High)* |  | *-* | *$2,374,090* |

a As total magnitude of these estimates is less than 2% of total health benefits, this analysis uses mean values for health benefits with a range.

Table 20 presents the health benefits from mortality incidences. Section 3.3 explains and presents the calculated values of the high and low end of mortality incidences due to reduced wood smoke. The EPA recommended mean VSL ($7.4 million) and standard deviation ($4.7 million) inform the high and low end of the VSL. These EPA VSL estimates are converted from 2007$ to 2010$ using a 7% discount rate.

Table 20 Total Health Benefits from Mortality Incidents (2010$)

|  |  |  |  |
| --- | --- | --- | --- |
| Health Incident Avoided | VSL | Cases | Economic Value (2010$, 7% discount rate) |
| Adult Mortality (low) | Low End | 3,091,230 | 12.46 | $93,610,148  |
| Adult Mortality (high) | High End | 13,853,290 | 28.23 | $238,084,165  |
| Infant Mortality | Low End | 3,091,230 | 0.03 | $248,204  |
| High End | 13,853,290 | 0.03 | $415,599  |
| *Total Health Benefits (low)* | $93,858,352  |
| *Total Health Benefits (high)* | $238,499,764  |

The total potential savings from a DHP energy efficiency program is the product of the total candidate homes for DHP and the per unit savings from DHP installation. These per unit savings, presented in Table 21, are RTF approved estimates.

Table 21 Total Regional Savings Potential from a DHP Conversion Program

|  |  |  |
| --- | --- | --- |
| Heating Zone | Number ofZonal Electric Homes | Potential Electric Savings |
| **Zonal to DHP Conversion** |
| **Each Home (kWh)a** | **Region Total (GWh)** |
| 1 | 407,986 | 3,522 | 1,437 |
| 2 | 111,150 | 3,341 | 371 |
| 3 | 34,559 | 3,143 | 109 |
| Total | 553,695 | - | 1,917 |

a Electric savings vary by heating and cooling zone. This report uses an average savings value per heating zone for the purposes of this analysis.

The sum of mortality and morbidity health benefits from Table 19 and Table 20 provide a high and low end of reduced wood smoke health benefits from running a DHP program. This total health benefit divided by the total savings potential gives us the dollars benefit per kWh electric energy saved by the program. Table 22 presents this calculation.

Table 22 Derivation of $ Benefit per kWh Saved by the DHP Program

|  |  |  |
| --- | --- | --- |
| Total Health Benefits (2010$)a | Regional Total Savings Potential (GWh) | $/ kWh Saved |
| Low | $94,970,497 | 1,917 | $0.05 |
| High | $240,873,853 | $0.13 |

a The sum of low and high end mortality and morbidity benefits in Table 19 and Table 20 provide the high and low end of total health benefits.

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1. Ecotope, Inc., 2013. *Ductless Heat Pump Impact & Process Evaluation: Billing Analysis.* Northwest Energy Efficiency Alliance (NEEA).

https://www.neea.org/docs/default-source/reports/ductless-heat-pump-impact-process-evaluation--billing-analysis-report.pdf?sfvrsn=6 [↑](#footnote-ref-1)
2. EPA (U.S. Environmental Protection Agency), 2009. Integrated Science Assessment for Particulate Matter.

http://www.epa.gov/ttn/naaqs/standards/pm/s\_pm\_2007\_isa.html [↑](#footnote-ref-2)
3. Ibid. p. 7.96. [↑](#footnote-ref-3)
4. A simple calculation presented to the RTF by Ecotope Consulting indicated health benefits of reduced wood smoke could exceed the value of the electricity saved by the DHP measure. [↑](#footnote-ref-4)
5. Abt Associates, 2014. Memorandum to the RTF. Final Summary of the Methodology and Results of Estimating the Health Impacts of Displacing Wood Heat with Electricity in the Pacific Northwest. [↑](#footnote-ref-5)
6. COBRA is a free screening level tool available on the EPA website: http://epa.gov/statelocalclimate/resources/cobra.html#what

According to the EPA “COBRA does not replace regulatory quality analyses. COBRA serves as a preliminary screening tool to identify those scenarios that might benefit from further evaluation with the more sophisticated air quality modeling approaches that are currently available” [↑](#footnote-ref-6)
7. EPA (U.S. Environmental Protection Agency), 2009. Integrated Science Assessment for Particulate Matter. [↑](#footnote-ref-7)
8. http://www.epa.gov/ttn/naaqs/standards/pm/s\_pm\_2007\_isa.html Ecotope, Inc., 2013. *Ductless Heat Pump Impact & Process Evaluation: Billing Analysis.* Northwest Energy Efficiency Alliance (NEEA). [↑](#footnote-ref-8)
9. For this example, an eligible home is one with electric resistance zonal heating. [↑](#footnote-ref-9)
10. Values for Douglass fir, from http://forestry.usu.edu/htm/forest-products/wood-heating. [↑](#footnote-ref-10)
11. See Appendix A of <http://cta.ornl.gov/bedb/pdf/BEDB4_Full_Doc.pdf>. [↑](#footnote-ref-11)
12. The EPA Residential Wood Combustion report provides data on heating appliance types and wood types burned at the county level. It also provides emission rates from each wood burning appliance in terms of tons of pollutant released per ton of wood burned. While there is some uncertainty in these appliance efficiencies, the science behind them is well understood and tested in the laboratory. [↑](#footnote-ref-12)
13. The COBRA model relies on the source – receptor (S-R) Matrix for dispersion modeling. This matrix defines the relationship between an emission source and annual pollutant concentration at a single receptor in each county, located at the center of the county. As per the COBRA manual, the S-R Matrix method is a screening tool that provides crude estimate of pollutant concentrations. Limited S-R Matrix validation literature exists. The S-R Matrix is informed by the Climatological Regional Dispersion Model and was calibrated using EPA Federal Reference Method pollutant monitoring sites. Relative to more sophisticated and resource-intensive three-dimensional modeling approaches, this model does not fully account for all the complex chemical interactions that take place in the atmosphere in the secondary formation of PM2.5. Instead, it relies on more simplistic species dispersion-transport mechanisms supplemented with chemical conversions at the receptor location. [↑](#footnote-ref-13)
14. Correspondence with Abt Associates. [↑](#footnote-ref-14)
15. EPA (U.S. Environmental Protection Agency), 2009. Integrated Science Assessment for Particulate Matter.

http://www.epa.gov/ttn/naaqs/standards/pm/s\_pm\_2007\_isa.html [↑](#footnote-ref-15)
16. Cal. EPA (California Air Resources Board, California Environmental Protection Agency), 2010. *Estimate of Premature Deaths Associated with Fine Particle Pollution (PM2.5) in California Using a U.S. EPA Methodology*. Pages 4-9 <http://www.arb.ca.gov/research/health/pm-mort/pm-report_2010.pdf> [↑](#footnote-ref-16)
17. Cal EPA (California Air Resources Board, California Environmental Protection Agency), 2008. *Methodology for Estimating Premature Deaths Associated with Long-term Exposure to Fine Airborne Particulate Matter in California*. Pages 13-16. http://www.arb.ca.gov/research/health/pm-mort/PMmortalityreportFINALR10-24-08.pdf [↑](#footnote-ref-17)
18. EPA (U.S. Environmental Protection Agency), 2009. Integrated Science Assessment for Particulate Matter. p. 15. http://www.epa.gov/ttn/naaqs/standards/pm/s\_pm\_2007\_isa.html [↑](#footnote-ref-18)
19. Lepeule J, F Laden, D Dockery, J Schwartz, 2012. Chronic exposure to fine particles and mortality: an extended follow-up of the Harvard Six Cities study from 1974 to 2009. *Environ Health Perspectives*, Vol. 120(7), pp. 965-970. [↑](#footnote-ref-19)
20. Krewski D, M Jerrett, RT Burnett, R Ma, E Hughes, YL Shi, M Turner, CA Pope, GD Thurston, EE Calle, MJ Thun, 2009. Extended Follow-Up and Spatial Analysis of the American Cancer Society Study Linking Particulate Air Pollution and Mortality. Health Effects Institute. [↑](#footnote-ref-20)
21. EPA (U.S. Environmental Protection Agency), 2013. User’s Manual for the Co-Benefits Risk Assessment (COBRA) Screening Model, Version 2.61.

http://epa.gov/statelocalclimate/documents/pdf/cobra-2.61-user-manual-july-2013.pdf [↑](#footnote-ref-21)
22. COBRA manual, Appendix F. http://epa.gov/statelocalclimate/documents/pdf/cobra-2.61-user-manual-july-2013.pdf [↑](#footnote-ref-22)
23. U.S. EPA. (2012). Regulatory Impact Analysis for the Final Revisions to the National Ambient Air Quality Standards for Particulate Matter. EPA-452/R-12-005. December 2012. Research Triangle Park, NC: Office of Air and Radiation, Office of Air Quality Planning and Standards. [↑](#footnote-ref-23)
24. Woodruff, T. J., Grillo, J., & Schoendorf, K. C. (1997). The relationship between selected causes of postneonatal infant mortality and particulate air pollution in the United States. *Environmental Health Perspectives, 105*(6), 608-612. [↑](#footnote-ref-24)
25. “Guidelines for Preparing Economic Analysis – Appendix B” National Center of Environmental Economics, US EPA. (Dec. 2010, Updated May, 2014) [↑](#footnote-ref-25)
26. The U.S. Office of Management and Budget (OMB) suggests using a VSL between $1 and $ 10 million for all government agencies (Office of Management and Budget, circular A-4). The Food and Drug Administration uses a VSL of $5 million (not adjusted for inflation and the real income year). This estimate is roughly in the middle of the OMB suggested range. The Center for Medicare and Medicaid Services uses a VSL of $ 5 million as well, citing that it is in the middle of the OMB provided range (“How US Government Agencies Value Mortality Risk Reductions” Lisa A. Robinson (2003)). The Department of Transportation relies on nine wage risk studies for its VSL estimates (published in 2004 or later). In a recent update, the Department of Transportation updated its VSL estimate to a value very similar to the EPA. Adjusting for income, and year, the Department of Transportation VSL is $9.1 million, compared to EPA’s value of $9.2 million (2012 $) (Robinson, Lisa A., and James K. Hammitt. 2014. “Research Synthesis and the Value per Statistical Life.” Regulatory Policy Program Working Paper RPP-2014-14. Cambridge). [↑](#footnote-ref-26)
27. RTF Wood Smoke Subcommittee Meeting Notes (4/10/2014) http://rtf.nwcouncil.org/subcommittees/WoodSmoke/meetings.asp. [↑](#footnote-ref-27)
28. “Age Differences in the Value of Statistical Life – Revealed Preference Evidence” Aldy and Viscusy (April 2007). Discussion Paper, Resources for the Future. [↑](#footnote-ref-28)
29. SAB Advisory on EPA's Issues in Valuing Mortality Risk Reduction. (October 12, 2007) <http://nepis.epa.gov/Adobe/PDF/P10007U3.PDF> [↑](#footnote-ref-29)
30. It should be noted that there may be some confirmation bias that influences studies to estimate VSL within an order of magnitude. As this report did not attempt to review each VSL calculation in detail, this statement is only intended as a caution. [↑](#footnote-ref-30)
31. Ecotope, Inc., 2013. *Ductless Heat Pump Impact & Process Evaluation: Billing Analysis.* Northwest Energy Efficiency Alliance (NEEA).

https://www.neea.org/docs/default-source/reports/ductless-heat-pump-impact-process-evaluation--billing-analysis-report.pdf?sfvrsn=6 [↑](#footnote-ref-31)
32. The negative savings values in zone-2 and zone-3 homes with wood heat are not statistically significant (the negative signs may be artifacts of statistical error). However, the differences between these savings values and those of homes without wood heat are much too large to be explained by statistical error. [↑](#footnote-ref-32)
33. See Ecotope 2013 *Ductless Heat Pump Impact & Process Evaluation: Billing Analysis* for the full analysis that leads to this conclusion [↑](#footnote-ref-33)
34. One example is the ducted heating system, which requires fan energy and loses heat through leaky ducts. Another example is the heat pump, which can deliver thermal energy in quantities that are greater than the amount of electric energy used to power the heat pump. [↑](#footnote-ref-34)
35. Using the Residential Building Stock Assessment, we can estimate the average efficiency of wood burning devices in the region. We discuss this in greater detail below but do not consider the issue to be a major obstacle to the quantification of wood heat. [↑](#footnote-ref-35)
36. Krewski D, M Jerrett, RT Burnett, R Ma, E Hughes, YL Shi, M Turner, CA Pope, GD Thurston, EE Calle, MJ Thun, 2009. Extended Follow-Up and Spatial Analysis of the American Cancer Society Study Linking Particulate Air Pollution and Mortality. Health Effects Institute. [↑](#footnote-ref-36)
37. Krewski D, M Jerrett, RT Burnett, R Ma, E Hughes, YL Shi, M Turner, CA Pope, GD Thurston, EE Calle, MJ Thun, 2009. Extended Follow-Up and Spatial Analysis of the American Cancer Society Study Linking Particulate Air Pollution and Mortality. Health Effects Institute. [↑](#footnote-ref-37)
38. Lepeule J, F Laden, D Dockery, J Schwartz, 2012. Chronic exposure to fine particles and mortality: an extended follow-up of the Harvard Six Cities study from 1974 to 2009. *Environ Health Perspectives*, Vol. 120(7), pp. 965-970. [↑](#footnote-ref-38)
39. For clarity and simplicity, we describe the model in terms of discrete time units, though continuous-time models are more common in research applications. The distinction is not important to our current objective. [↑](#footnote-ref-39)
40. We express the results in approximate terms to avoid the more cumbersome notation used by researchers. [↑](#footnote-ref-40)
41. In Krewski et al, 2009, see equation 3 on page 16 and the surrounding discussion; the parameter value, 0.006, is from Table 4 on page 126 of the same reference. [↑](#footnote-ref-41)
42. In the Krewski study, the adult mortality variable was defined in terms of deaths of individuals age 30 and above. [↑](#footnote-ref-42)
43. As explained in (EPA 2013, Appendix F) COBRA model the deaths due to a single year’s air quality change as being distributed over a 20-year span beginning in that year. This distribution affects valuation through monetary discount rates but it does not affect the expected change in the number of deaths. [↑](#footnote-ref-43)
44. The monetary value of any proposition is only meaningful if people are willing to pay for the proposition. Furthermore, we can only estimate the value if we have insight into *how much* they would pay for it. In placing a value on a change in mortality risk, we must take special care to ensure that we have insight into how much people would pay for the type of change being offered. [↑](#footnote-ref-44)