Human Health Benefits of Reducing Residential Wood Smoke Emissions in Puget Sound Energy's Service Territory

FINAL REPORT

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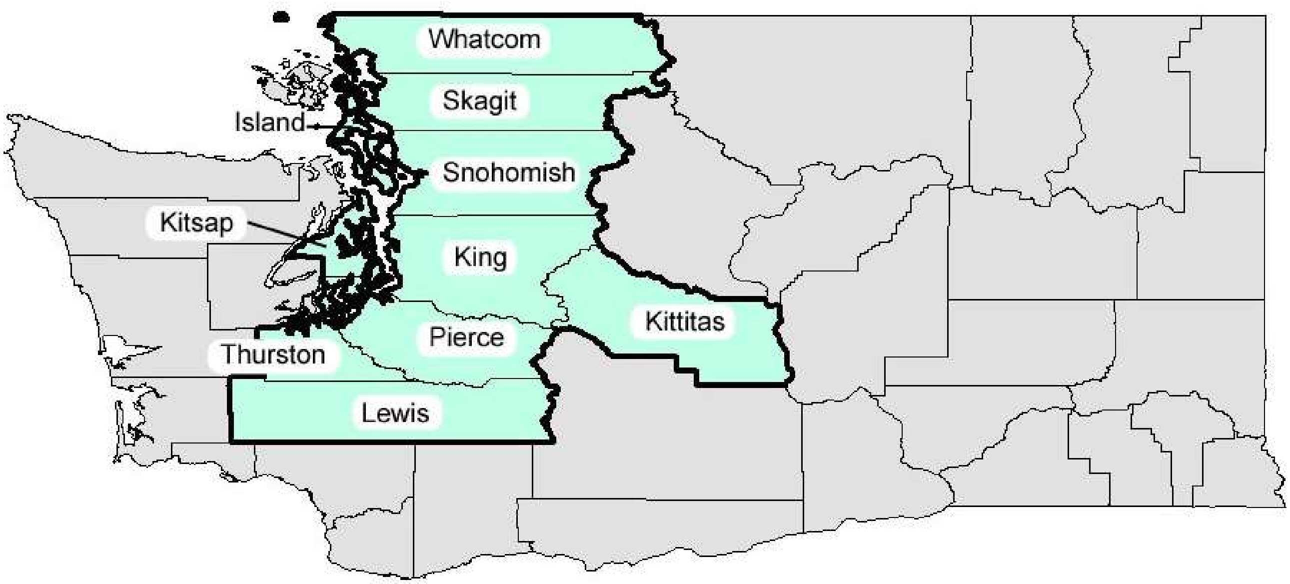
1. Introduction

This report summarizes the methods and results of the analysis Abt Associates (Abt) performed to estimate the economic value of the public health improvements from reducing wood smoke emissions in year 2017 in the Puget Sound Energy (PSE) electric service territory, shown in Figure 1. Recommendations to PSE on appropriate interpretation and use of these results are also provided.

Figure 1. Counties in the Puget Sound Energy Service Territory



This study uses the same data sources and similar methodology as the 2014 study that Abt Associates conducted for the Regional Technical Forum for the Pacific Northwest. A summary of that methodology is included in the RTF report entitled, "Quantifying the Health Benefits of Reduced Wood Smoke from Energy Efficiency Programs in the Pacific Northwest."[1] The objective of the current study is to apply a methodology similar to the RTF regional study, but confine the study area to the PSE electric service territory.

In addition to this introduction, there are five sections: Section 2 describes the objectives of the study; Section 3 outlines the data and methodologies used to estimate the baseline wood smoke emissions, the change in emissions and air quality, and the resulting economic value of the public health improvements in the PSE service territory modeled using the Co-Benefits Risk Assessment (COBRA) Screening Model[2]; Section 4 summarizes the results of the analysis; Section 5 contains the conclusions and a discussion that focuses on the appropriate interpretation of the results, uncertainties and limitations of the analysis, and recommendations for future studies; and Section 6 provides acknowledgments.

[1] Preliminary Report: Quantifying the Health Benefits of Reduced Wood Smoke from Energy Efficiency Programs in the Pacific Northwest, RTF Staff Technical Report, November 4, 2014, available at https://nwcouncil.app.box.com/s/fcsq182d73t7lqyyiz070rrni19y7gxo(accessed June 2018).

[2] http://epa.gov/statelocalclimate/resources/cobra.html

2. Objectives

The objectives of this study are to estimate the economic value of the public health improvements from reducing residential wood burning from supplemental wood heating appliances in the Puget Sound Energy service territory[3] and to present the results as $/kWh of electricity conserved by ductless heat pumps (DHPs) replacing zonal electric heat. The reduction in residential wood burning assumes that 80 percent of households in the PSE service territory with zonal electric heating will reduce supplemental wood heating due to the installation and use of ductless heat pumps.

3. Technical Approach

This section describes the overall technical approach and task specific methodologies. Details are provided below.

3.1. Overview

Particulate matter (PM) is the term used for a mixture of solid particles and liquid droplets found in the air; fine particles ($PM_{2.5}$) are smaller than 2.5 micrometers (millionths of a meter) in aerodynamic diameter. Wood combustion emits PM particles directly into the air, known as primary PM emissions. In addition, wood combustion emits other gases, such as sulfur dioxide (SO_2) and nitrogen oxides (NO_x), which undergo chemical reactions in ambient air to form sulfate and nitrate particles. These particles, known as secondary PM emissions, make up a large proportion of the fine particle pollution in most parts of the country. A substantial body of published scientific literature acknowledges a correlation between elevated $PM_{2.5}$ and increased incidence of illness and premature mortality.[4]

Emissions of NO_x may also contribute to ground-level ozone formation and associated adverse health outcomes; however, the relative balance of volatile organic compounds (VOCs) and NO_x at a particular location determines whether NO_x behaves as a net ozone generator or a net ozone inhibitor. Due to the complexity in ozone formation chemistry, assessment of changes in ozone levels requires advanced air quality modeling (e.g., using a Community Multiscale Air Quality [CMAQ] Modeling System). On the other hand, changes in ambient $PM_{2.5}$ can be assessed using simplified air quality modeling (such as the S-R matrix built into the COBRA Screening Model), which is less resource-intensive and permits running multiple scenarios relatively quickly. Additionally, most epidemiological evidence points toward particulate matter as a stronger causal agent for mortality and morbidity than ground-level ozone.[5] Furthermore, road transportation is the most significant contributor to ozone formation. Thus, accounting for ozone would substantially increase the cost of this project without adding significant value to the study. Therefore, this study focuses exclusively on health impacts from changes in $PM_{2.5}$ concentrations.

The analysis includes a year 2017 scenario where a specified number of homes, defined by the airshed boundary, reduce or eliminate wood combustion in supplemental heating appliances. The analysis follows the four-step framework outlined in Figure 2 to estimate the health benefits in year 2017 within the Puget Sound Energy service territory. Specifically:

- The analysis uses the Regional Technical Forum methodology[6] and EPA's Residential Wood Combustion Tool[7] in conjunction with local data provided by Puget Sound Energy to model year-specific baseline

[3] RCW 80.52.030(8) defines system costs as an estimate of all direct costs of a resource over its effective life, including …. such quantifiable environmental costs and benefits as are directly attributable to the resource.

[4] Mangia, C., Cervino, M., Gianicolo, E.A.L. 2015. Secondary Particulate Matter Originating from an Industrial Source and Its Impact on Population Health. *International Journal of Environmental Research and Public Health* 12: 7667-7681.

[5] Caiazzo, F., Ashok, A. Waitz, I., et al. 2013. Air pollution and early deaths in the United States. Part I: Quantifying the impact of major sectors in 2005. *Atmospheric Environment* 79: 198-208.

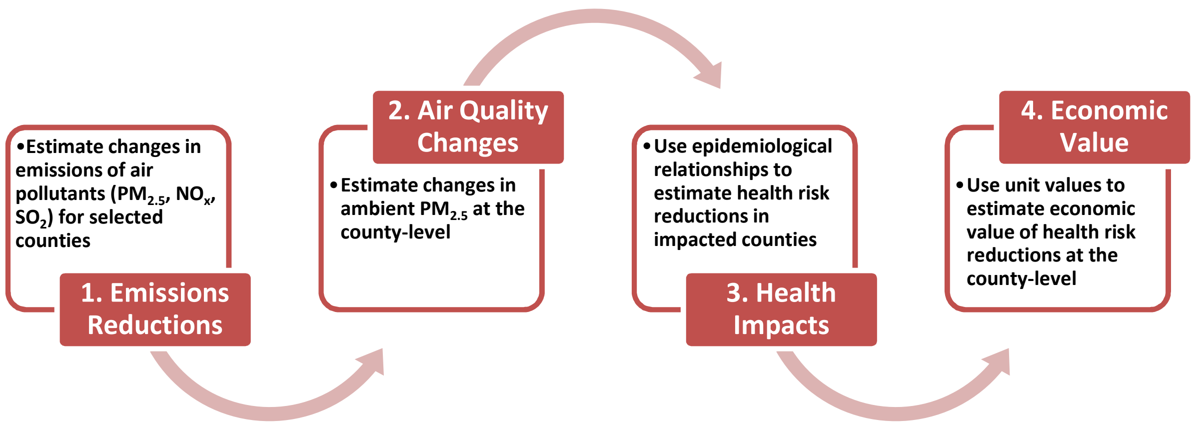
[6] Preliminary Report: Quantifying the Health Benefits of Reduced Wood Smoke from Energy Efficiency Programs in the Pacific Northwest, RTF Staff Technical Report, November 4, 2014, available at https://nwcouncil.app.box.com/s/fcsq182d73t7lqyyiz070rrni19y7gxo(accessed June 2018).

[7] EPA's Residential Wood Combustion Tool (2014_RWC_v3.0_28apr2016.zip) is available for download at ftp://ftp.epa.gov/EmisInventory/2014/doc/nonpoint/.

emissions from residential wood combustion and subsequent reductions in direct $PM_{2.5}$, NO_x, SO_2, VOC and NH_3 emissions from reductions in wood combustion (Step 1 of the framework Figure 2);

- These emissions changes are then input into EPA's Co-Benefits Risk Assessment (COBRA) Screening Model[8] to produce year- and scenario-specific estimates of reductions in the ambient $PM_{2.5}$ concentrations at the county level (Step 2 of the framework in Figure 2). The COBRA model is also used to estimate reductions in human health risks and the economic value of these risk reductions (Steps 3–4 of the framework in Figure 2). For most data inputs required in these steps, the analysis used default COBRA values. However, data provided by Puget Sound Energy is used to refine COBRA population projections and income growth databases, such that they reflect the broader set of energy planning assumptions in the Puget Sound Energy service territory.

Figure 2. Health Benefits Analysis Framework



Note that estimating the change in electricity consumption and associated air pollutant emissions and health impacts from replacing supplemental wood heating with zonal electric heating is not modeled in this project. In addition, the reduced wood purchasing costs and increased electricity costs are not considered in this analysis.

3.2. Estimating Baseline Emissions

Abt used the U.S. Environmental Protection Agency's (U.S. EPA) Residential Wood Combustion (RWC) Tool and data from a Northeast Energy Efficiency Alliance (NEEA) DHP pilot program[9] to estimate baseline wood smoke emissions in the Puget Sound Energy service territory. Note, however, that since the COBRA model is a county-level resolution model, the boundary of the PSE airshed is defined by the following county boundaries: Island, King, Kitsap, Kittitas, Lewis, Pierce, Skagit, Snohomish, Thurston and Whatcom.

The U.S. EPA, with support from Abt Associates, developed the RWC Tool to estimate the emissions from residential wood combustion for its National Emissions Inventory (NEI). Every three years the NEI includes revised emission estimates for nonpoint sources,[10] such as residential wood combustion, using the best available

[8] The COBRA model is available for download at https://www.epa.gov/statelocalenergy/co-benefits-risk-assessment-cobra-health-impacts-screening-and-mapping-tool

[9] Ecotope, Inc., 2013. *Ductless Heat Pump Impact & Process Evaluation: Billing Analysis*. Northwest Energy Efficiency Alliance (NEEA). https://neea.org/docs/default-source/reports/ductless-heat-pump-impact-process-evaluation--billing-analysis-report.pdf?sfvrsn=6 (accessed January 2018).

[10] Nonpoint sources are small stationary sources of air pollution which by themselves may not emit very much, but collectively their emissions can be of concern—particularly where large numbers of sources are located in heavily populated areas. Nonpoint sources are also referred to as area sources and are generally too small or too numerous to be inventoried individually.

data and methodologies. The RWC Tool is a Microsoft Access tool that estimates the number of wood burning appliances in each county in the United States in 11 different categories (Table 1) and then uses this appliance count to estimate county-level residential wood smoke pollutant emissions.

Table 1. Wood burning appliances included in the EPA RWC Tool.

#	Wood Burning Appliance
1	Fireplaces
2	Woodstove: fireplace inserts; non-EPA certified
3	Woodstove: fireplace inserts; EPA certified; non-catalytic
4	Woodstove: fireplace inserts; EPA certified; catalytic
5	Woodstove: freestanding, non-EPA certified
6	Woodstove: freestanding, EPA certified, non-catalytic
7	Woodstove: freestanding, EPA certified, catalytic
8	Woodstove: pellet-fired
9	Furnace: Indoor, cordwood-fired, non-EPA certified
10	Wood-fired boiler
11	Outdoor wood burning device (e.g. firepits, chimineas)

The RWC Tool relies on survey data from the U.S. Census Bureau's American Housing Survey[11] to estimate the fraction of households in each county that use each appliance, and multiplies that fraction by the number of occupied houses in each county. The tool also determines the amount of wood burned (cords or pellets) by heating type (primary and supplemental heating). Burn rates are estimated by applying climate zone-based adjustment factors to national average burn rates obtained from the U.S. Forest Service documents,[12] which synthesize information from state residential wood consumption surveys, or from more detailed state, local, or tribal (S/L/T) agency data supplied to EPA.[13] The type-specific amounts of wood burned are converted into a uniform unit of tons using county-level data on the density of firewood supplied by the U.S. Forest Service.[14] The tons of wood burned are then used to estimate emissions of 36 pollutants, including criteria pollutants and hazardous air pollutants (HAPs) using EPA-approved emission factors.[15]

In cases where the estimated PSE service territory baseline emissions reductions, calculated using data from the NEEA DHP pilot program, exceed the baseline emissions estimates from the RWC Tool, the data from the pilot

[11] U.S. Census Bureau. American Housing Survey. http://www.census.gov/programs-surveys/ahs/ (accessed January 2018)

[12] U.S. Forest Service, available at http://www.ncrs.fs.fed.us/pubs/ (accessed January 2018)

[13] County-level climate zones are used to adjust burn rate profiles to account for the fact that less wood is burned in warmer states. The Commercial Buildings Energy Consumption Survey (CBECS) climate zones are groups of climate divisions, as defined by the National Oceanic and Atmospheric Administration (NOAA), which are regions within a state that are as climatically homogeneous as possible. Each NOAA climate division is placed into one of five zones based on its 30-year average heating degree-days (HDD) and cooling degree-days (CDD) for the period 1971 through 2000. Burn rates for all SCCs in the national default are multiplied by the ratio of the average British thermal unit (Btu) consumption to heat a house in each climate zone to the average Btu consumption in climate zone 1. The ratios are 0.30 for climate zone 5, 0.44 for climate zone 4, and 0.77 for climate zone 3.

[14] Density is calculated using the U.S. Forest Service Timber Products Output data for fuel wood consumption. Average density of fuel wood for each county is calculated by dividing total mass of fuel wood consumed by total volume. http://www.fia.fs.fed.us/program-features/tpo/ (accessed January 2018)

[15] The emission factors for fireplaces and wood stoves are based on EPA's AP-42 Compilation of Air Pollutant Emission Factors. https://www.epa.gov/air-emissions-factors-and-quantification/ap-42-compilation-air-emission-factors (accessed January 2018). Emission factors for wood-fired furnaces and pellet stoves are from the Mid-Atlantic Regional Air Management Association 2002 Emissions Inventory. http://www.marama.org/technical-center/emissions-control-analysis/overview/el-improvements-projects/residential-wood-combustion (accessed January 2018)

program are used to adjust the RWC Tool emissions upwards. Since the pilot program data are local data, it is reasonable to assume that the local data are more accurate than the U.S. Census Bureau's survey data. Emissions of direct $PM_{2.5}$, NOx, SO_2, VOC and NH_3 emissions are then aggregated by county across all appliances to determine the total baseline wood smoke emissions for each pollutant in each county.

3.2. Estimating Emissions Reductions

To estimate emissions reductions, Abt Associates used the RTF method for estimating the amount of wood saved by climate zone due to DHP installations. The estimation method is based on data from the NEEA DHP pilot program. 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; and
- Metering data for about 100 program homes.

Using this data, the RTF estimated the percent of the heat load met with non-utility supplemental fuels (cord-wood, wood pellets, and propane) both pre and post-DHP installation. The difference between these estimates was then used to estimate the supplemental fuel savings associated with DHP installation. The results are summarized in Table 2 below.

Table 2. Estimated Supplemental Fuel Savings from Ductless Heat Pumps

Heating zone	Percent of load met with supplemental fuel (homes with supplemental heat)		Average supplemental fuel savings per DHP (energy delivered to space, kWh equivalent)	
	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

Next, to estimate the air pollutant emissions changes of a DHP program focused on replacing zonal electric heat, PSE provided Abt Associates with the total estimated single family housing units by county in the PSE service territory that have both zonal electric heating and a wood heating appliance. The estimate is based on data from the Residential Building Stock Assessment (RBSA)[16] using data for the greater Puget Sound Region in Washington State. Since burning propane does not generate significant quantities of $PM_{2.5}$, this study only focuses on appliances burning cord-wood and wood pellets.

Data on fuel consumption and the types of heating appliances used throughout the region are available in the NEEA DHP pilot program as well as EPA's Residential Wood Combustion Tool. These are combined with estimates of average appliance efficiency and fuel energy content to inform estimates of potential fuel savings (in terms of tons of wood and tons of pellets) resulting from the installation of DHPs. For this savings estimate, Abt Associates applied the same assumptions as RTF:

- The average cord-wood appliance is 50 percent efficient, and cord-wood averages 13,760 kBtu/ton[17]; and

[16] Ecotope, Inc., 2012. *2011 Residential Building Stock Assessment: Single-Family Characteristics and Energy Use*. Northwest Energy Efficiency Alliance (NEEA).

[17] Value for air-dried wood with 20% moisture content. (Source: Forest Products Laboratory fact sheet, http://www.fpl.fs.fed.us/documnts/techline/fuel-value-calculator.pdf).

- The average pellet stove is 85 percent efficient, and the average energy content of a ton of pellets is 16,400 kBtu.[18]

Table 3 below provides the share of total supplemental fuel energy by fuel type and heating zone for cord-wood and wood pellets. The heating zones correspond to the Pacific Northwest heating zones defined by the Northwest Power & Conservation Council and range from mild heating requirements in zone 1 to substantial heating requirements in zone 3.

Table 3. Share of Total Supplemental Fuel Energy by Fuel Type and Heating Zone

	Share of total supplemental fuel energy	
Heating Zone	Wood	Pellets
1	59.7%	11.7%
2	49.9%	11.3%
3	53.7%	2.3%

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. Abt Associates calculated the absolute decrease based on potential tons of wood combustion reduction and data on wood burning appliances in the Pacific Northwest provided in EPA's Residential Wood Combustion Tool.

In summary, the total reduction in emissions from replacing supplemental wood heat for a single home in the PSE service territory is calculated as the reduction in tons of wood burned times a weighted average mix of emission factors by county from existing wood burning appliances in the region plus the reduction in tons of pellets burned times a pellet stove emissions factor:

$$\text{Emissions Reduction}_p \text{ (tons)} = (\text{wood reduction} * EF_{w,c,p}) + (\text{pellet reduction} * EF_p)$$

Where: Emissions Reduction$_p$ = reduction in emissions of pollutant p in tons for a home with both wood heat and zonal electric heat. The pollutants included in this study include direct $PM_{2.5}$, NO_x, SO_2, VOC and NH_3

Wood reduction = reduction in wood burned due to DHP installation (tons)

$EF_{w,c,p}$ = county-level weighted emissions factor for indoor wood burning appliances for pollutant p (tons p per ton of wood)

Pellet reduction = reduction in pellets burned due to DHP installation (tons)

EF_p = emissions factor for pellet stoves for pollutant p (tons of p per ton of pellets)

Abt Associates calculated the weighted average emission factors using emission factors provided in EPA's Residential Wood Combustion Tool. The analysis also assumes that the reduction in wood combustion due to the installation of DHPs is in the same proportion as the existing indoor wood appliance distribution.

To calculate total county-level emissions reductions, the emissions reductions by pollutant are multiplied by the number of estimated single family housing units in a county with zonal electric heating and a woodstove and a factor of 0.8 to convert total potential into achievable potential (i.e. the fraction of housing units where DHP installation will displace supplemental wood heating).

$$\text{Emissions Reductions}_{p,c} \text{ (tons)} = \text{Emissions Reduction}_p * HU_c * 0.8$$

[18] Ibid.

Where: Emissions $Reductions_{p,c}$ = reduction in emissions of pollutant p in tons for county c.

HU_c = number of housing units in county c with both zonal electric heating and a woodstove

0.8 = fraction of housing units where DHP installation will displace supplemental wood heating

The total emissions reductions in the PSE service territory are calculated by summing the county-level emissions reductions.

3.3. Estimating the Economic Value of Public Health Improvements from Reduced Wood Smoke in the PSE Service Territory

For estimating the economic value of public health improvements, Abt only considered health endpoints for which there is sufficient weight-of-evidence to infer a causal or likely-to-be causal relationship with $PM_{2.5}$. Abt employed a suite of epidemiological relationships that underlies EPA's recent $PM_{2.5}$ Regulatory Impact Analyses and reflects the results of EPA's PM Integrated Science Assessment (a document that received extensive review from the Clean Air Scientific Advisory Committee). Specifically, Abt estimated impacts on the following $PM_{2.5}$-related health endpoints:

- Premature mortality;
- Asthma exacerbations;
- Heart attacks;
- Respiratory hospital admissions;
- Acute Bronchitis;
- Respiratory symptoms;
- Asthma emergency department visits;
- Minor Restricted activity days;
- Work days lost.

The health impacts associated with the displacement of wood heat with DHPs are estimated using U.S. EPA's Co-Benefits Risk Assessment (COBRA) model. COBRA provides screening-level estimates of the impact of air pollution emission changes on ambient particulate matter ($PM_{2.5}$) air pollution concentrations, translates the changes in air quality into health effect impacts, and then monetizes these impacts. The COBRA User's Manual[19] provides detailed information on each component comprising the model: (i) a baseline emissions inventory (page 27); (ii) a simplified air dispersion model (Appendix A) ; (iii) a suite of health impact functions (Appendix C) ; and (iv) a matching suite of economic valuation functions to monetize health impacts (Appendix F). The health impact and valuation components are based on the assumptions currently used by EPA as reasonable best estimates. The current version of COBRA generates estimates of expected air quality and health impacts for the 2017 model year.

To carry out the health impacts analysis, Abt entered the calculated reductions in county-level emissions of $PM_{2.5}$, SO_2, NO_x, NH_3, and VOCs from wood combustion into the COBRA model. COBRA ran these changes in emissions through its air dispersion model to generate estimates of improvements in county-level air quality across the nation, as measured by decreases in annual average ambient $PM_{2.5}$ concentrations.[20]

[19] The COBRA User's Manual is available online at: https://www.epa.gov/sites/production/files/2017-10/documents/cobra_user_manual_september2017_508_v2.pdf (accessed January 2018)

[20] COBRA models air quality impacts across the United States by default. For the present analysis, however, most air quality impacts would occur in the PSE service territory and adjacent areas.

For the health effects, COBRA combined the estimated county-level improvements in air quality with 2017 population estimates using the health impact and valuation functions to generate county-level estimates of the number of avoided cases for each adverse health effect, and the associated economic values.

Note that the COBRA outputs include low and high estimates for the changes in the number of cases and the corresponding economic values for adult mortality, non-fatal heart attacks, and total health effects. The low and high estimates are derived using different assumptions about the sensitivity of adult mortality and non-fatal heart attacks to changes in ambient $PM_{2.5}$ levels. Specifically, the high estimates are based on studies that estimated a larger effect of changes in ambient $PM_{2.5}$ levels on the incidence of these health effects. The low and high estimates were derived as follows:

- For adult mortality, EPA (2009)[21] recently used two studies when analyzing proposed NO_2 national ambient air quality standards and presented the results separately for each study. Thus, COBRA reports results based on the two studies separately as well. In the health effects table, the low estimate of adult mortality is based on Krewski et al. (2009)[22] and the high estimate is based on Lepeule et al. (2012).[23] See Appendix C of the COBRA User Manual for further details on the two studies.
- For non-fatal heart attacks, the low estimate is based on Peters et al. (2001).[24] The high estimate was derived by pooling the effect estimates from four studies: Sullivan et al. (2005),[25] Pope et al. (2006),[26] Zanobetti et al. (2009),[27] and Zanobetti & Schwartz (2006).[28] See Appendix C of the COBRA User Manual for further details.
- For total health effects, the low estimate is the sum of the low estimates of adult mortality and non-fatal heart attacks, plus the single estimates for all other health effects. The high estimate of total health effects is the sum of the high estimates of adult mortality and non-fatal heart attacks, plus the single estimates for all other health effects.

For the present analysis, Abt made adjustments to the standard COBRA health effect and valuation outputs to make the results consistent with PSE's projected population and income for 2017. The specifics of these adjustments are detailed in the subsections below.

Because some of the health benefits from reductions in 2017 emissions are expected to occur in years after 2017 (see page F-6 of the COBRA User's Manual), COBRA discounts the estimated stream of economic benefits to the year 2017 using either a 3% or a 7% discount rate, in accordance with Office of Management and Budget (OMB) guidelines. In this report, the results are presented using a 7% discount rate.

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[21] U.S. EPA. (2009). *Proposed NO_2 NAAQS Regulatory Impact Analysis (RIA).* Research Triangle Park, NC.: Office of Air and Radiation, Office of Air Quality Planning and Standards Retrieved from http://www.epa.gov/ttn/ecas/ria.html.

[22] Krewski, D., Jerrett, M., Burnett, R. T., Ma, R., Hughes, E., Shi, Y., Tempalski, B. (2009). Extended follow-up and spatial analysis of the American Cancer Society study linking particulate air pollution and mortality. *Res Rep Health Eff Inst*(140), 5-114; discussion 115-136.

[23] Lepeule J, Laden F, Dockery D, Schwartz J. Chronic exposure to fine particles and mortality: an extended follow-up of the Harvard Six Cities study from 1974 to 2009. Vol 120(7). 965-970.

[24] Peters, A., Dockery, D. W., Muller, J. E., & Mittleman, M. A. (2001). Increased particulate air pollution and the triggering of myocardial infarction. *Circulation, 103*(23), 2810-2815.

[25] Sullivan, J., Sheppard, L., Schreuder, A., Ishikawa, N., Siscovick, D., & Kaufman, J. (2005). Relation between short-term fine-particulate matter exposure and onset of myocardial infarction. *Epidemiology, 16*(1), 41-48.

[26] Pope, C. A., 3rd, Muhlestein, J. B., May, H. T., Renlund, D. G., Anderson, J. L., & Horne, B. D. (2006). Ischemic heart disease events triggered by short-term exposure to fine particulate air pollution. *Circulation, 114*(23), 2443-2448.

[27] Zanobetti, A., Franklin, M., & Schwartz, J. (2009). Fine particulate air pollution and its components in association with cause-specific emergency admissions. *Environmental Health 8*, 58-60.

[28] Zanobetti, A., & Schwartz, J. (2006). Air pollution and emergency admissions in Boston, MA. *J Epidemiol Community Health, 60*(10), 890-895. doi: 60/10/890 [pii] 10.1136/jech.2005.039834 [doi]

Adjustments in Projected Population

To compute the number of cases of adverse health effects avoided, COBRA health impact functions rely on: (i) the estimated change in probability of the health effect as a result of lower exposure to air pollution, which is based on epidemiological evidence; and (ii) the projected size of the affected population in 2017. The 2017 population estimates in COBRA are based on projections by Woods & Poole Economics, Inc. (see Appendix E of the COBRA User's Manual). On the other hand, PSE has its own projections of 2017 population in the PSE service territory.

To ensure that the estimated health impacts in the PSE service territory are consistent with PSE's projections, Abt adjusted COBRA outputs using county-level ratios of the PSE 2017 population projections (supplied by PSE) to the COBRA 2017 population projections. Abt derived these county-level adjustment ratios separately for each health effect, since the health impact functions are specific to different age groups. The relevant age groups and simple average (across counties) of the ratios for each health effect are presented in Table 4.

Table 4. Age Groups and Average Population Adjustment Ratios for Health Effects

Health Incident Avoided	Age Group	Average Population Ratio
Adult Mortality (low)	30-99	1.0182
Adult Mortality (high)	25-99	1.0195
Non-Fatal Heart Attacks (low, high)	18-99	1.0187
Infant Mortality	0	0.9994
Hospital Admissions (Respiratory)	0-99	1.0138
Hospital Admissions (Cardiovascular-related)	18-99	1.0187
Asthma Emergency Room Visits	0-99	1.0138
Acute Bronchitis	8-12	0.9994
Respiratory Symptoms (Upper)	9-11	0.9994
Respiratory Symptoms (Lower)	7-14	0.9994
Asthma Exacerbations (attacks, shortness of breath, and wheezing)	6-18	0.9994
Minor Restricted Activity Days	18-64	1.0196
Work Loss Days	18-64	1.0196

Abt then multiplied the county-level number of avoided cases of each health effect reported by COBRA with the respective population projection adjustment ratios, to generate estimates that are better aligned with the PSE 2017 population projections.

Adjustments in Income Growth

Abt made a second adjustment to account for the differences in the projected 2017 income per capita. The default COBRA values for each health endpoint (called "unit values") are presented in Table 5. They are based on published estimates of the costs of treating the illness (can include both direct medical costs and costs of lost productivity) and the willingness-to-pay (WTP) to avoid the illness or to reduce the risk of premature death (i.e., value per statistical life, VSL). The unit values based on WTP estimates reflect expected growth in real income over time. This is consistent with economic theory, which argues that WTP for most goods (such as health risk reductions) will increase if real incomes increase. Empirical evidence in the U.S. suggests that the WTP for reduced health rises at a slower rate than real income, which is captured by the income elasticity of this WTP.

Table 5. Health Effects and their Economic Values (2010$/case)

Health Incident Avoided	Economic Value (2010$)
Time-varying costs[a]	
Adult Mortality[b] (3% discount rate)	$8,434,924
Adult Mortality[b] (7% discount rate)	$7,512,853
Non-Fatal Heart Attacks (3% discount rate)	$33,259 - $263,795
Non-Fatal Heart Attacks (7% discount rate)	$31,446 - $253,247
Costs incurred in the year of exposure	
Infant Mortality[b]	$9,401,680
Hospital Admissions (Respiratory, Cardiovascular-related)	$15,430 - $41,002
Asthma Emergency Room Visits	$388 - $464
Acute Bronchitis	$477
Respiratory Symptoms (Upper, Lower)	$21 - $33
Asthma Exacerbations (attacks, shortness of breath, and wheezing)	$57
Minor Restricted Activity Days	$68
Work Loss Days	$160

a. In COBRA, most health effects and their economic values are expected to occur in the year of analysis. However, since all avoided cases of adult mortality are not expected 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 in each year are discounted to present terms.

b. Following EPA (2012),[29] COBRA assumes that some of the incidences of premature adult mortality related to $PM_{2.5}$ 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.[30]

The income growth adjustments in COBRA followed the approach used by EPA (2005, p. 4-17)[31] and account for real income growth between the year of the WTP estimate (i.e., 1990 for the WTP estimates in COBRA) and the year for which benefits are estimated (i.e., 2017). EPA (2005, p. 4-18) used different income elasticity estimates to adjust the WTP for: minor health effects (0.14); severe and chronic health effects (0.45); and premature mortality (0.40). Income growth adjustments to WTP were performed using the following equation:

$$WTP_{2017} = WTP_{1990} \times (Income_{2017} / Income_{1990})^{Elasticity}$$

COBRA uses income growth adjustment factors supplied by EPA for the valuation of mortality and other health endpoints. However, these factors are national estimates and are not consistent with the growth in income per capita in the PSE service territory, as expected by PSE. Thus, for the analysis of wood smoke emissions in the PSE service territory, Abt used the projected 2017 income data (supplied by PSE) to generate income projection adjustment factors. Specifically, Abt calculated the ratio of the PSE data-based income growth adjustment factors to the factors supplied by EPA, and applied this income projection adjustment ratio to obtain the unit values that reflect expected income per capita growth for the PSE service territory.

[29] 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.

[30] 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.

[31] U.S. EPA. (2005). Regulatory Impact Analysis for the Final Clean Air Interstate Rule. Research Triangle Park, NC: Office of Air Quality Planning and Standards (OAQPS), Emission, Monitoring, and Analysis Division and Clean Air Markets Division.

The income growth factors used in COBRA and the average income projection adjustment ratios used in the current analysis are presented in Table 6.

Table 6. Calculation of Income Adjustment Factors

Estimate	Minor Health Effect	Severe and Chronic Health Effect	Premature Mortality
COBRA Adjustment Factor	1.058	1.198	1.174
2017 Income per capita, 2005$ (PSE data)	$24,511	$24,511	$24,511
1990 Income per capita , 2005$ (U.S. Census)	$26,875	$26,875	$26,875
New Adjustment Factor [a]	0.985	0.956	0.960
Elasticity Estimate EPA (2005, p. 4-18)	0.14	0.45	0.40
Income Projection Adjustment Ratio [b]	**0.931**	**0.798**	**0.818**

a. New Adjustment Factor = (2017 Per Capita Income from PSE / 1990 Per Capita Income from Census) $^{\text{Elasticity}}$

b. Income Adjustment Ratio = New Adjustment Factor / COBRA Adjustment Factor

Abt performed the income projection adjustment for the following health effects:

- **Minor Health Effect:** acute bronchitis, asthma exacerbations, minor restricted activity days, and upper and lower respiratory symptoms.
- **Premature Mortality:** adult mortality, infant mortality.

3.4. Determination of Benefits per kWh of Electricity Saved by Replacing Zonal Electric Heat with Ductless Heat Pumps

Abt computed the ratio of the total monetized health benefits estimated by COBRA for the entire PSE service territory (in 2010$, at 7% discount rate) to the amount of electricity (in kilowatt-hours [kWh]) saved by replacing zonal electric heat with ductless heat pumps (DHPs) in the PSE service territory in 2017. Because the analyzed scenarios involved concurrent reductions in wood smoke emissions from all counties in the PSE service territory, the health benefits in any particular county come from reductions in wood smoke emissions in the county itself as well as in the other counties of the PSE service territory. Therefore, the results of this analysis should not be used to derive estimates of health benefits per kWh for individual counties.

The amount of electricity savings per household when replacing zonal electric heat with DHPs is estimated using data from the NEEA DHP pilot program.

Abt assumed that all zonal electric heat would be replaced with DHPs, with a coefficient of performance (COP) of 3, which represents the average COP for DHPs in the PSE service territory.[32] Abt calculated the amount of electricity (kWh) saved when replacing zonal electric heat with DHPs using the following equation:

Electricity Savings (kWh) = Usable heat from zonal electric heating (kWh) - (Usable heat from zonal electric heating (kWh) / DHP COP)

The monetized health benefit (in 2010$, at 7% discount rate) per 1 kWh saved is estimated by dividing the total economic value of health benefits for the PSE service territory with the amount of electricity saved by the installed DHPs across the PSE service territory in 2017. Note that in the benefits-per-kWh calculation, the benefits are not adjusted to account for the emissions resulting from increased electricity generation, because this estimation is outside the scope of this analysis. In addition, the achievable potential for DHP installation is assumed to be 80% of homes with zonal electric heat.

[32] Baylon, D. B. Larson, P. Storm, K. Geraghty. Ductless Heat Pump Impact & Process Evaluation: Field Metering Report. Report by Ecotope Inc. to the Northwest Energy Efficiency Alliance. http://neea.org/docs/default-source/reports/ductless-heat-pump-impact-process-evaluation-field-metering-report.pdf?sfvrsn=31 (accessed January 2018).

4. Results

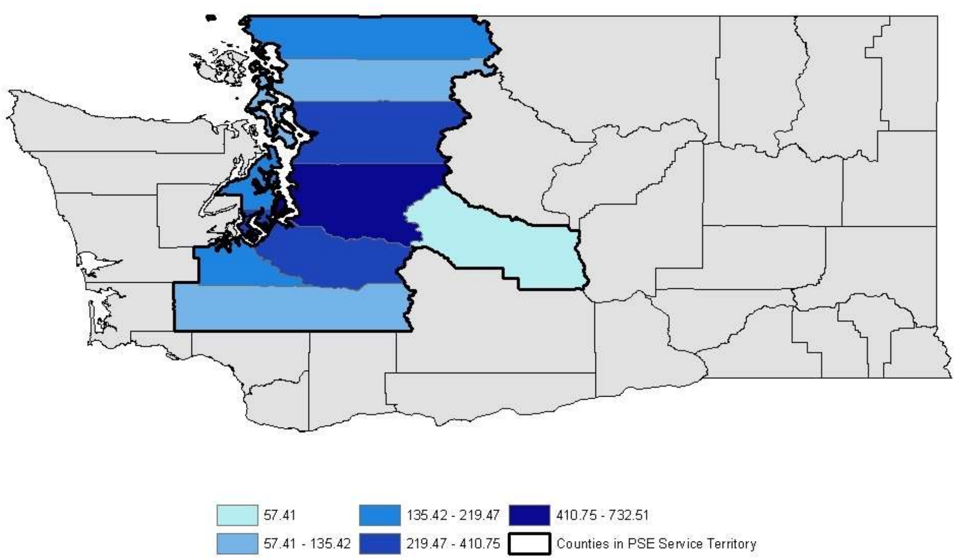
This section describes the results of estimating the baseline emissions, emissions reductions, change in air quality and resulting economic value of public health improvements. Abt Associates cautions against generalizing the results of the DHP analysis to other energy efficiency measures as more research is needed to determine the extent to which other energy efficiency measures impact supplemental wood heating.

4.1. Baseline Emissions

The baseline emissions of $PM_{2.5}$ from residential wood combustion in the PSE service territory in 2017 range from 57.41 tons in Kittitas County to 732.51 tons in King County. Since the emissions baseline is primarily driven by the appliance population and appliance population is correlated with total human population, more populated counties are likely to have higher emissions. Therefore, a similar trend to $PM_{2.5}$ emissions is seen across other pollutants, where the lowest emissions are in Kittitas County and the highest emissions are in King County. For example, NO_x emissions range from 6.28 tons in Kittitas County to 111.89 tons in King County. The year 2017 baseline residential wood smoke $PM_{2.5}$ emissions in the PSE service territory are shown by county in

Figure **3**.

Figure 3. Year 2017 Baseline Residential Wood Smoke $PM_{2.5}$ Emissions in the PSE Service Territory (tons)

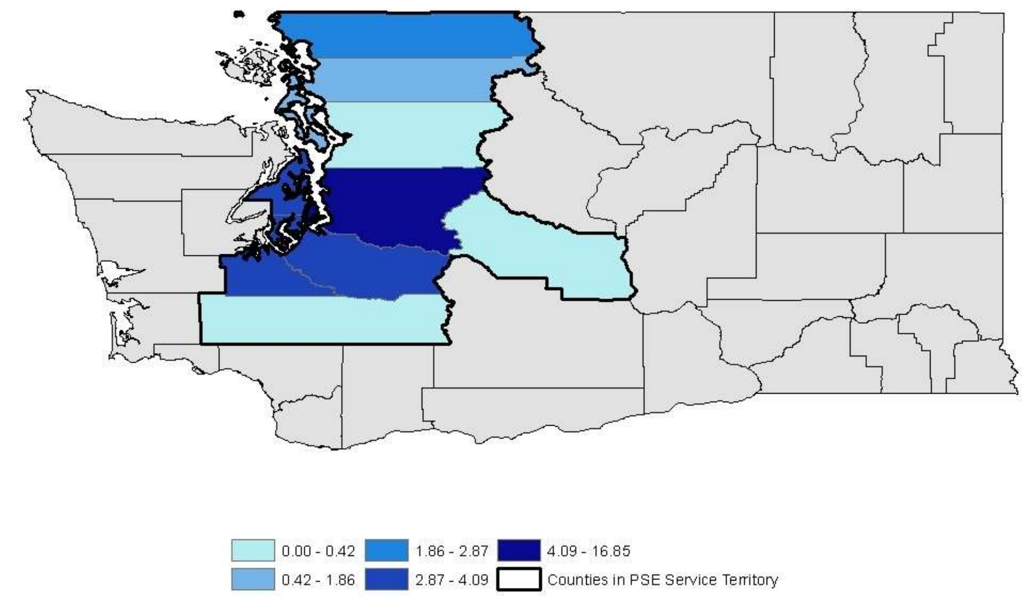


4.2. Emissions Reductions and Air Quality Impacts

The $PM_{2.5}$ emissions reductions resulting from displacing zonal electric heating with DHPs in 80% of homes in the PSE service territory with zonal electric heating are shown in

Figure **4**. The $PM_{2.5}$ emissions reductions in 2017 range from 0 tons in Lewis and Snohomish Counties to 4.09 tons in Thurston County.

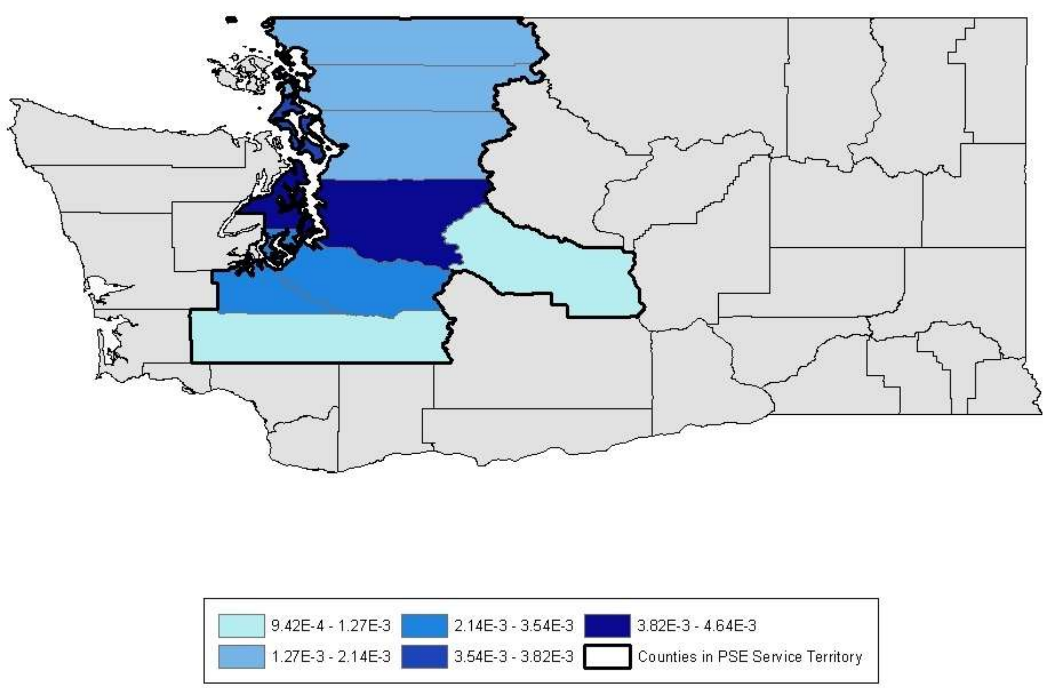
Figure 4. Year 2017 Residential Wood Smoke $PM_{2.5}$ Emissions Reductions in the PSE Service Territory (tons)



The improvements in ambient air quality (µg/m^3 $PM_{2.5}$) due to the reduction in supplemental wood heating in homes where DHPs replacezonal electric heating in the PSE service territory are shown in

Figure 5. The ambient air quality improvements range from 9.42E-04 µg/m^3 $PM_{2.5}$ in Kittitas County to 4.64E-3 µg/m^3 $PM_{2.5}$ in Kitsap County.

Figure 5. Improvements in Ambient Air Quality (µg/m^3 $PM_{2.5}$) due to Reductions in 2017 Wood Smoke Emissions in the PSE Service Territory



4.3. Economic Value of Public Health Improvements

The results from COBRA show a decrease in ambient pollution levels due to decreases in wood smoke emissions (

Figure 5),[33] which drives the effects on human health.

Table 7 contains estimates of the health benefits and their economic values (2010$, 7% discount rate) for each health effect in the PSE service territory. Maps of the monetized total health benefits are shown in

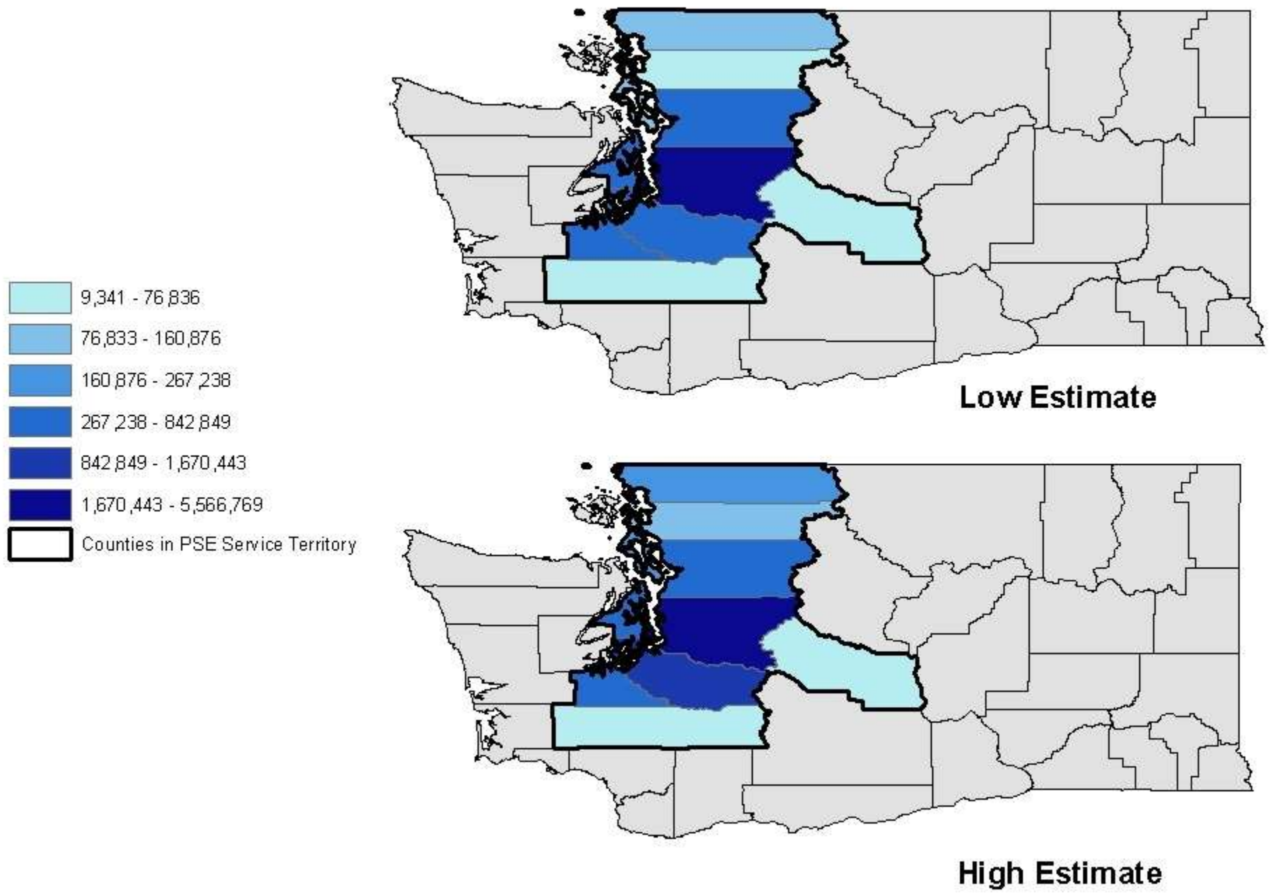
[33] Figure 4 shows changes in $PM_{2.5}$ emissions. Maps of other pollutants are not shown because the spatial distribution of the percent reduction in emissions is the same across pollutants.

Figure 6. The reduction in emissions from supplemental wood combustion in homes where DHPs replaced zonal electric heat in 2017 resulted in a range of total health benefit estimates within the PSE service territory of $4.523 - $10.305 million (2010$, 7% discount rate) for 2017. The main driver of the monetized health benefits is the avoided premature mortality among adults, which constituted 98% of the total monetized health benefits.

Table 7. Improvements and Monetized Improvements in Health Outcomes for the PSE Service Territory from Reductions in 2017 Wood Smoke Emissions in the Service Territory

Health Incident Avoided	80% Reduction in Supplemental Wood Heat from Houses with Zonal electric heating	
	Number of Cases Avoided	Economic Value (2010$, 7% discount rate)
Adult Mortality (low)	0.6	$4,431,324
Adult Mortality (high)	1.4	$10,149,825
Infant Mortality	0.0	$10,864
Non-fatal Heart Attacks (low)	0.1	$7,668
Non-fatal Heart Attacks (high)	0.6	$71,254
Respiratory Hospital Admissions	0.1	$3,742
Cardiovascular Hospital Admissions	0.2	$6,256
Acute Bronchitis	1.1	$501
Upper Respiratory Symptoms	19.1	$629
Lower Respiratory Symptoms	13.4	$279
Asthma ER Visits	0.3	$130
Minor Restricted Activity Days	628.6	$42,563
Work Loss Days	110.7	$17,678
Asthma Exacerbations	19.5	$1,120

Figure 6. Total Health Benefits (2010$, 7% Discount Rate, Low and High Estimate) from Reductions in 2017 Wood Smoke Emissions in the PSE Service Territory



4.4. Benefits per kWh Saved by DHPs

When assessing the benefits per kWh of electricity saved by DHPs displacing zonal electric heat, the benefits range from \$0.020 – \$0.045 per kWh of electricity saved by DHPs per year (2010\$). The upper bound of electricity saved when displacing all zonal electric heating in the PSE service territory with DHPs is provided in

Table **8**. The main factors driving the benefits per kWh saved are the number of houses within the service territory with both zonal electric heat and a wood burning appliance, the heating zone where these houses are located, and the population experiencing a reduction in exposure to wood smoke pollution.

Table 8. Maximum Potential Electricity Savings (kWh) Associated with Replacing Zonal Electric Heating in the PSE Service Territory with Ductless Heat Pumps

County	Maximum Potential Electricity Savings (kWh)
Island	9,824,959
King	133,528,945
Kitsap	32,339,073
Kittitas	3,518,198
Lewis	0
Pierce	31,881,635
Skagit	15,395,741
Snohomish	0
Thurston	33,719,087
Whatcom	23,694,849
TOTAL	**283,902,488**

5. Conclusions and Limitations of the Analysis

This analysis suggests that there are potentially significant health benefits from a reduction in wood smoke emissions—up to $10.3 million per year when replacing zonal electric heat with DHPs in 80% of homes with zonal electric heat in the PSE service territory. Similar to the RTF regional study, the total monetized health benefits are driven primarily by avoided mortality, which accounts for more than 98% of the monetized health impacts. The results suggest that there would be between 0.6 and 1.4 avoided deaths over a 20-year period from emissions reductions in 2017. As expected, these values are lower than the RTF regional study since the PSE service territory is a subset of the Pacific Northwest region. In addition, the current study is only evaluating a reduction in wood burning from houses with zonal electric heat whereas the RTF regional study examined the benefits of reducing wood burning across all homes with wood burning appliances, regardless of the home's primary heat source.

When the health benefits are compared with the amount of electricity saved when displacing zonal electric heat with ductless heat pumps, the results suggest a benefit of $0.020–$0.045 per kWh across the PSE service territory per year (2010$). This value is the amount of benefit-per-kWh of electricity saved when displacing zonal electric heating with DHPs.

It should be emphasized that these results represent an impact of fixed percentage reduction of wood smoke emissions occurring *concurrently* in all counties of the *PSE service territory*. Analysis of scenarios defined in this manner is not designed to yield meaningful estimates of county-level benefits-per- kWh. This is because the health benefits in a given county are dependent on the reductions in wood smoke emissions in all counties of the PSE service territory. To confirm this, Abt performed a supplementary COBRA analysis in a prior study for the RTF subcommittee for four separate counties. For each county, two COBRA runs were executed: (1) emissions were reduced only in a given county, but not in the remaining study area; (2) emissions were reduced in all counties of the study area except the county of interest. The analysis showed that a significant portion of the benefits in any given county results from emission reductions occurring outside that county.

To estimate county-level benefits-per- kWh, it would be necessary to implement a set of county-specific COBRA analyses for each county in the PSE service territory. One could also develop benefits-per- kWh estimates for a group of counties in the PSE service territory by analyzing concurrent reductions in wood smoke emissions in this group of counties alone, while keeping emissions in all other counties at their baseline levels.

The present results are subject to two limitations (addressing these limitations are outside the scope of this project):

(1) The total health benefits estimates do not reflect the impact from additional emissions associated with increased electricity generation required to power the DHPs. Therefore, there is an upward bias in the reported estimates of the total health benefits and benefits-per- kWh.

(2) The benefits-per- kWh estimates do not include the costs of purchasing, installing, and operating DHPs or any administrative costs of implementing a widespread program to reduce wood smoke emissions. These emission reductions could be achieved through some combination of:

   a. Incentives, including programs to incentivize residents to switch out older, dirtier wood-burning devices for electric heat pumps or newer, cleaner-burning wood appliances;
   b. Education of residents on methods of burning wood to minimize emissions, such as through the U.S. EPA's Burn Wise program;[34] and
   c. Regulation, such as burn bans, in which local governments forbid wood burning, typically on days with poor air quality.

   Each of these options has implementation costs, which should be compared with the estimated benefits of reduced emissions from wood smoke to determine the net benefits of any proposed program.

It is also important to note the limitations of the COBRA tool. As a screening tool, COBRA provides an approximation of the benefits from emission reduction scenarios, allowing scenario comparisons along the dimensions of: improvements in air quality (expressed by lower concentrations of ambient $PM_{2.5}$); improvements in public health outcomes; or economic value of these health improvements. As discussed above, COBRA returns results as a range, with low- and high-end estimates, based on different assumptions about the sensitivity of adult mortality and non-fatal heart attacks to changes in ambient $PM_{2.5}$ concentrations. These ranges should be analyzed separately rather than averaged or otherwise summarized to determine a central value.

Moreover, these ranges do not capture all uncertainty surrounding the estimates, including uncertainty in the value of a statistical life (VSL), which is used to monetize the benefits of avoided mortality, as well as uncertainty in population forecasts, the source-receptor matrix used in the analysis, or in the baseline emissions estimates.[35] Another source of uncertainty in COBRA estimates relates to whether there is regional variability in some inputs. Because COBRA health impact and valuation functions represent national-level relationships, accuracy of regional-level analyses may be improved by identifying region-specific relationships from the literature. (Further details on uncertainty in COBRA inputs are provided in the appendices of the COBRA User's Manual.)

More accurate estimates of the benefits of reductions in wood smoke emissions would require a more sophisticated air dispersion modeling approach, such as using the Comprehensive Air Quality Model with Extensions (CAMx). It is possible that improved air dispersion modeling could actually slightly increase the estimated benefits. The COBRA modeling found small (but nonzero) air quality benefits in states far from the PSE service territory; an improved air dispersion model could concentrate these benefits in the PSE service territory. Additional analysis using a more advanced air dispersion model could also examine the effects of other air pollutants, such as ground-level ozone. These pollutants are not included in the COBRA model, but could be important drivers of additional health benefits.

[34] http://www.epa.gov/burnwise/

[35] Although this analysis used the best-available data to estimate wood smoke emissions, these estimates are also somewhat uncertain. Better data on wood burning appliance usage in the study area could improve the emissions estimates.

Regardless, this analysis is an important first step in understanding the benefits of reducing residential wood smoke emissions in the PSE service territory. The initial results suggest that there could be significant health benefits from replacing zonal electric heat with DHPs. Additional research can help refine these estimates beyond the screening-level results presented here by addressing some of the uncertainties discussed above.

6. Acknowledgements

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