AN EXPLORATION OF OWN AND CROSS-PRICE ELASTICITY OF DEMAND FOR RESIDENTIAL HEATING IN THE FAIRBANKS NORTH STAR BOROUGH

By

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Abstract

The purpose of this study is to utilize community level household energy consumption data to determine the short-run own- and cross-price elasticity of heating oil and wood using the proportionally calibrated almost idea demand system model. Elasticity values can identify how residents of the Fairbanks North Star Borough will potentially alter home heating practices in response to a change in home heating oil price. Results indicate that values for own-price elasticity for oil is -0.259, with a 95% confidence interval of [-0.272, -0.246]. Based on predicted values a 1% increase in the price of heating oil is estimated to result in a reduction of 0.259% in the quantity of residential heating oil consumed by the average household. Cross-price elasticity estimates of wood with respect to a change in the price of oil is 0.198 with a 95% confidence interval of [0.171, 0.234]. Based on predicted values, a 1% increase in the price of oil is predicted to increase wood consumption by 0.198%.

In addition, this study utilized a Monte Carlo Simulation with estimated elasticity parameters to predict the change in household level energy consumption of wood and heating oil given an increase in heating oil prices. Approximately 71% of households are predicted to decrease overall energy consumption. 83.5% of households are predicted to decrease oil consumption, and 57.3% of houses are predicted to increase wood consumption. Through evaluating household's energy consumption decisions in the face of changing prices, these results can inform effective air quality policies.

Table of Contents

Page

Acknowledgements i

Abstract ii

List of Tables iv

List of Figures v

Abbreviations vi

Introduction 1

Background Information 2

Theoretical Framework 10

Analytical Framework: PCAIDS Model 12

Data 15

Analysis and Results 21

Further Consideration: Monte Carlo Simulation 28

Discussion 34

Conclusion and Future Research 37

References 40

Appendix 44

List of Tables

Page

Table 1: Comparison of Key Emission Factors and Sulfur Content for Fairbanks Heating Fuels..3

Table 2: National PM2.5 Ambient Air Quality Standards.. 6

Table 3: Fairbanks PM2.5 Ambient Air Measurements 2012-2015.. 7

Table 4: Variable Descriptions 17

Table 5: Market Prices, Expenditures, and Shares 18

Table 6: Total Household Energy consumption in mmBTU and Heating Degree Days............. 19

Table 7: Dependent Shares Models 21

Table 8: Aggregate Demand Model.. 22

Table 9: Mean Estimates of Own- and Cross-Price Elasticity Estimates for Heating Oil and Wood.. 23

Table 10: Median Estimates of Own- and Cross-Price Elasticity Estimates for Heating Oil and Wood.. 24

Table 11: Own- and Cross-price elasticity of Households Collecting vs. Purchasing Wood 26

Table 12: Oil Price Elasticity Estimates in Literature 27

Table 13: Summary of Monte Carlo Inputs 29

Table 14: Change in Household Energy Consumption... 30

Table 15: Change in Household Energy Expenditure ($)... 31

List of Figures

Page

Figure 1: Estimated tons per year of PM2.5 from Residential Sources 4

Figure 2: Weather Inversion 8

Figure 3: FNSB Air Quality Control Zone Boundaries 9

Figure 4: Distribution of Change in Net Household Energy Expenditure ($) 32

Figure 5: Distribution of Net Change in Household Energy Consumption (mmBTU)................ 33

Abbreviations

ADEC	Alaska Department of Environmental Conservation
AIDS	Almost Ideal Demand System
AQCZ	Air Quality Control Zone
BACM	Best Available Control Measure
BTU	British thermal unit
CAA	Clean Air Act
CCHRC	Cold Climate Housing Research Center
EPA	US Environmental Protection Agency
FSNB	Fairbanks North Star Borough
HS	High Sulfur
NAAQS	National Ambient Air Quality Standards
PCAIDS	Proportionally Calibrated Almost Ideal Demand System
PM	Particulate Matter
PM2.5	Particulate Matter with a diameter less than 2.5 micrometers
ULS	Ultra-low Sulfur

Introduction

On April 28th, 2017 the Environmental Protection Agency (EPA) re-classified the Fairbanks North Star Borough (FNSB) as a serious nonattainment area for the 2006 24-hour Particulate Matter (PM)2.5 National Ambient Air Quality Standards (NAAQS) under the Clean Air Act (CAA). The FNSB has recorded some of the highest levels of PM2.5 in the United States. When this reclassification occurred, it prompted the requirement for Alaska to conduct a Best Available Control Measure (BACM) analysis. The BACM analysis looks at control measures implemented throughout the U.S. to control PM2.5. Two of the policies being considered for the BACM is a mandated switch to Ultra-low Sulfur (ULS) or High Sulfur (HS) No. 1 from HS No. 2 in the FNSB PM2.5 non-attainment area (ADEC, 2019a). Alaska Department of Environmental Conservation (ADEC) estimates the price differential of about 33.5 cents/gallon from HS No. 1 to ULS, and a price differential of 0.07 cents/gallon from HS No. 2 to HS No. 1.

Using community household energy consumption data and prices, this examination seeks to estimate the short-run own- and cross-price elasticities of demand of heating oil and wood use. Motivation for this research is analyzing the possible impacts of the potential PM2.5 pollution control policy mandating FNSB households to transition to ULS, or HS No.1 heating oil in the Fairbanks PM2.5 serious non-attainment area (ADEC, 2019b). How household wood energy consumption might change, if the price of home heating oil increases through the mandated transition to ULS or HS No. 1, is of particular interest given the need to improve local air quality.

Price elasticities of energy demand have become increasingly relevant in determining the economic and environmental effects of energy policies on countries and communities alike.

Elasticity values can be used to help identify how residents of the FNSB will potentially alter home heating practices in response to a change in home heating oil price. This analysis draws on the "proportionally calibrated almost ideal demand system" (PCAIDS) developed by Epstein and Rubinfeld (2002) and presented by Coloma (2006) to estimate short-run elasticity values.

The remainder of this paper is as follows: background information on the history FNSB air quality and the Clean Air Act; discussion of demand system modeling as it pertains to the PCAIDS model; a review of the PCAIDS model and applications; Monte Carlo Simulation as an application and sensitivity analysis of results; presentation and discussion of results; implications of proposed policies; limitations of the analysis; and finally, conclusions and suggestions further research.

Background Information

In December of 2009, the EPA designated Fairbanks as a non-attainment area for PM2.5 emissions for the 2006 24-hour air quality standards. In December 2014, the state submitted the FNSB PM2.5 moderate attainment plan to the EPA which focused on potential actions toward meeting NAAQS. This plan focused on reducing emissions from residential heating sources, particularly wood stoves and hydronic heaters which are the main contributors to high PM2.5 levels in the FNSB (EPA, 2017a). *Table 1* summarizes emission factors per unit of fuel energy (in lb/mmBTU) to compare emissions across the range of solid, liquid and gaseous heating fuels used in Fairbanks.

Table 1: Comparison of Key Emission Factors and Sulfur Content for Fairbanks Heating Fuels

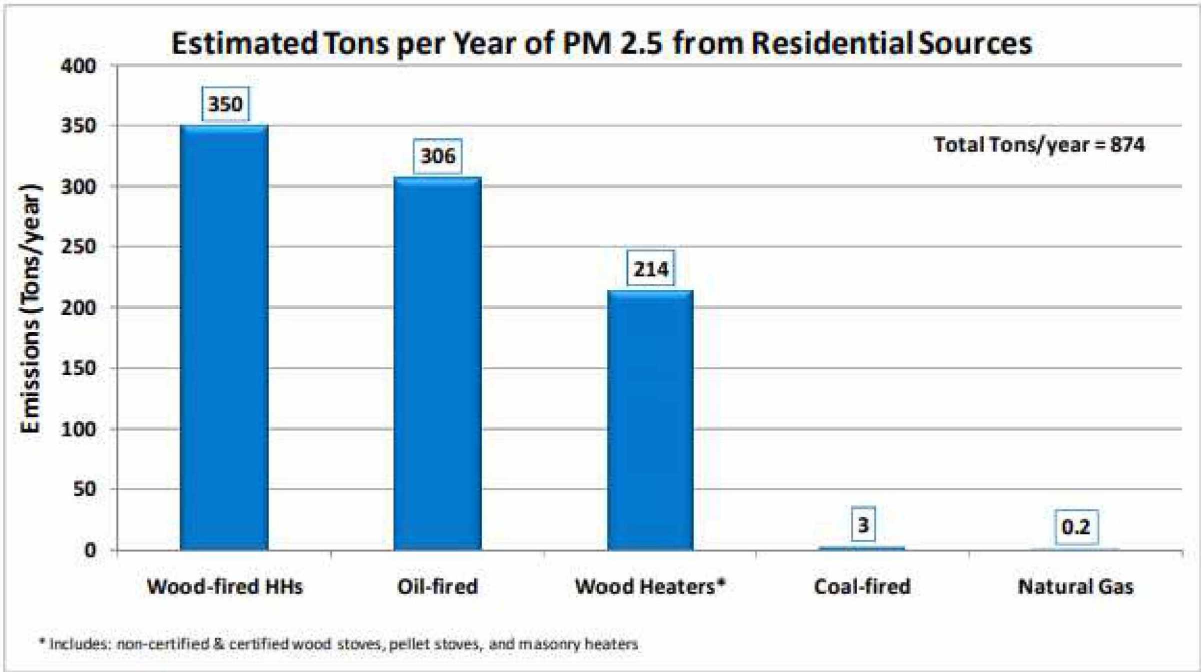
Fuel	**Emission Factor (lb/mmBTU)**		**Sulfur Content**
	$PM_{2.5}$	**SO_2**	**(ppmv)**
HS No. 1 & 2	0.00340	0.215	2,053
HS No. 1	0.00365	0.102	896
HS No. 2	0.00330	0.263	2,566
Natural Gas	0.00749	0.000591	<16
Coal	0.526	0.612	2,000
Wood Burning	0.18 – 2.0*	0.023	<500
ULS	~0.003-0.004	0.00171	15

ppmv = parts per million by volume
* Covering a range of uncertified and EPA-certified cordwood and pellet devices, assuming zero (oven dry) moisture content
Source: Sierra Research, Inc

As shown in *Table 1*, emission factors of $PM_{2.5}$ and Sulfur Dioxide $(SO)_2$ vary across the range of common heating fuels. PM2.5 emissions of wood-burning are significantly higher than HS No. 1 or No. 2 and ULS. PM2.5 emissions for wood is between 49 and 54 times higher per lb/mmBTU than HS No. 1. Above measurements are assuming zero moisture content in wood, if a household is burning wet wood, the PM2.5 emissions are generally far greater than dry wood. Considering the magnitude of difference between PM2.5 emissions of wood and heating oil, wood stoves are deemed to be "dirtier" than heating oil, making it the primary contributor to the PM2.5 emission non-attainment (ADEC, 2019c).

In 2009, Cold Climate Housing Research Center (CCHRC) conducted a study estimating PM2.5 Emissions from various residential sources. *Figure 1* displays total estimated tons of PM2.5 by residential wood type from the CCHRC study.

Figure 1: Estimated tons per year of PM2.5 from Residential Sources



Source: Reducing PM2.5 Emissions from Residential Heating Sources in the Fairbanks North Star Borough, CCHRC 2009

Based on the above graph, the largest emitter of PM2.5 emissions are wood-fired hydronic heaters at 350 tons/year, followed by oil-fired heaters at 306 tons/year, and finally wood heaters at 214 tons/year. By residential fuel type, wood emits 564 tons/year of PM2.5, making wood combustion the most significant source of PM2.5 emissions from residential heating sources.[1]

In 2015, the Borough approved mandatory curtailment programs to restrict the use of woodstoves during PM2.5 non-attainment levels. This program allows the FNSB and state to track weather and PM2.5 emissions to restrict the use of wood stoves when weather conditions are bad for air quality or public health. The moderate air quality plan included two additional remediation measures: requiring the removal of inefficient wood heating devices when a

[1] CCHRC notes that the rate of conversion of sulfur to PM2.5 in heating oil to PM2.5 in the atmosphere is unknown – whereas wood-burning devices almost exclusively emit PM2.5. Due to the uncertainty of the conversion rate of sulfur to PM2.5, it may be ill-advised to consider a policy to reduce sulfur emissions given reducing PM2.5 from wood-burning devices is more quantifiable.

property is sold, leased, or conveyed[2]; requiring commercial wood sellers to register with the state and disclose the moisture content of their wood.[3]

The EPA found that Fairbanks did not attain the standard based on 2013-2015 air quality data and were required to reclassify Fairbanks from “Moderate” to “Serious” non-attainment in April 2017. Currently, the FNSB is required to submit a BACM analysis and demonstrate attainment by December 31st, 2019.

In August of 2018, the FNSB passed the Home Heating Reclamation Act (HHRA). The Home Heating Reclamation Act states: *“the FNSB shall not regulate, prohibit, curtail, or issue fines or fees associated with, the sale, distribution, installation or operation of solid fuel heating appliances or combustible fuels. Sold fuel heating appliances include but are not limited to, wood stoves, coal stoves, wood-fired hydronic heaters, fireplace inserts, pellet fuel burning devices, and fireplaces*” (Resolution No. 2018-28)

The HHRA removes the FNSB’s ability to regulate wood stoves and other solid-fuel heating appliances. Due to the majority of the air quality issue being driven by wood-stoves and hydronic heaters, the inability of the FNSB to regulate solid-fuel heating appliances extends to the inability to control air quality. The HHRA moves the responsibility of regulating solid-fuel heating appliances to ADEC, and away from the borough.

The Clean Air Act (CAA) established in 1963 is a United States federal law designed to institute consistent air quality standards and protect the environment and human health from the

[2] Alaska State regulation. 18 AAC 50.077 and 18 AAC 50.079
[3] Alaska State regulation. 18 AAC 50.076(d)

effects of air pollution. The EPA, state, and local governments are required to monitor and enforce air quality regulations under the CAA.

The CAA established four major air quality goals: establish National Ambient Air Quality Standards (CAA § 109-110; USC § 7409-7410, 1990a), establish performance standards to determine appropriate levels of pollution allowed by different sectors in industry (Clean Air Act § 104-113; USC 7404-7413, 1990b), establish standards for controlling auto emissions (Clean Air Act § 201-219; USC § 7521-7554, 1990c), and help states develop plans to stay in compliance with the CAA (Clean Air Act § 301-328; USC § 7601-7627, 1990d).

NAAQS are allowable levels of harmful pollutants set by the EPA in accordance with the Clean Air Act. NAAQS are established for six primary pollutants which are: carbon monoxide, particulate matter (PM), lead, nitrogen dioxide, sulfur oxides, and ground-level ozone.[4] PM2.5 standards are presented in *Table 2* below.[5]

Table 2: National PM2.5 Ambient Air Quality Standards[6]

	Primary/Secondary	**Time**	**Level**	**Form**
PM2.5	Primary and Secondary	24 hours	35.0 $\mu g/m^3$	98th percentile, averaged over 3 years

Fairbanks PM2.5 air quality measurements using 2012-2015 annual mean, averaged over three years is presented in *Table 3* below.

[4] The Clean Air Act identifies two levels of Ambient Air Quality Standards, primary and secondary. Primary standards include the protection of sensitive groups such as asthmatics, children and elderly individuals. Secondary standards include protection from decreased visibility, animals, vegetation, and in some cases, structures.
[5] Air quality measurements taken at the Fairbanks State Office Building
[6] 40 CFR 50 Appendix N - see section 4.5(a), 4.5(b)

Table 3: Fairbanks PM2.5 Ambient Air Measurements 2012-2015

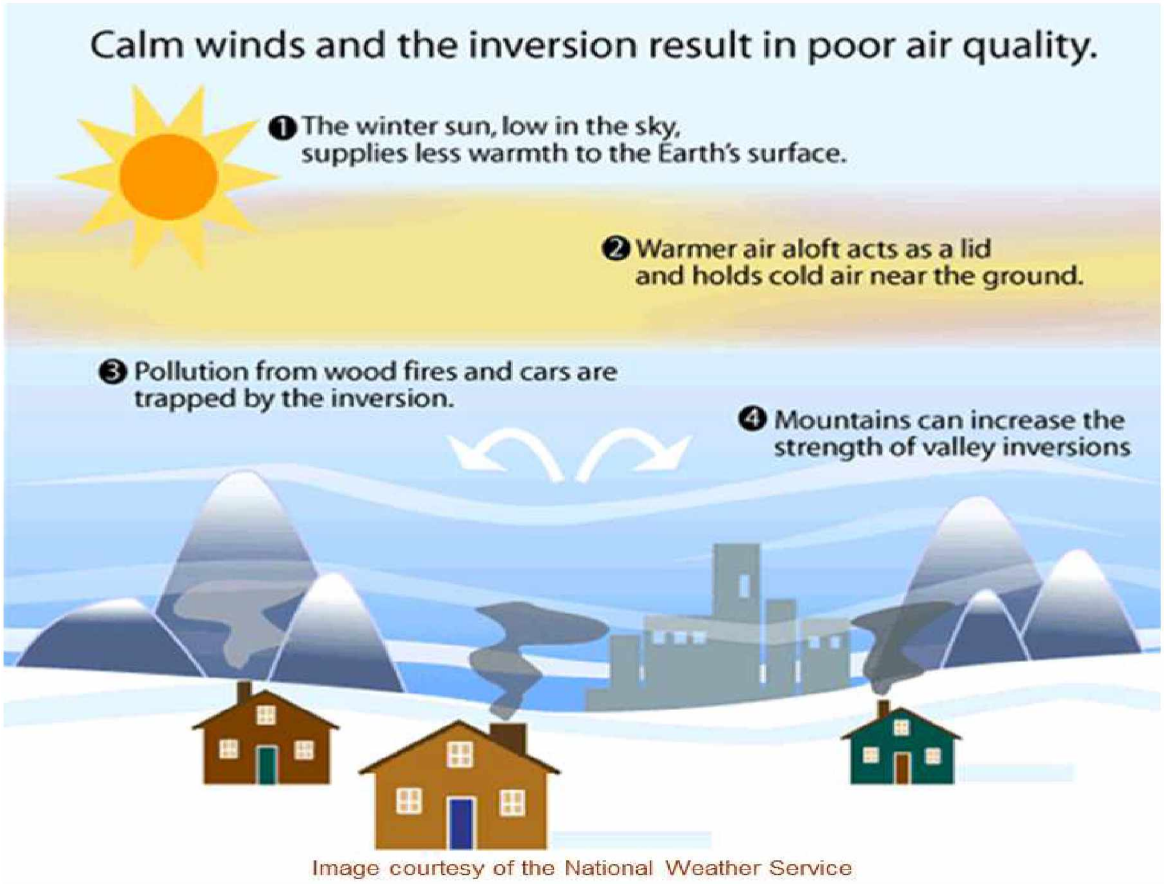
	Primary/Secondary	**Time**	**Level**	**Form**
PM2.5	Primary and Secondary	24 hours	39.0 $\mu g/m^3$	98th percentile, averaged over 3 years

The FNSB non-attainment zone was on average 4.0 $\mu g/m^3$ (micrograms per cubic meter) over the 2006 24hr PM2.5 emissions standard from 2012-2015. Overexposure to PM2.5 can cause respiratory and cardiovascular issues such as aggravation of asthma, decreased lung function, irritation of the airways, coughing and difficulty breathing, and irregular heartbeats. Individuals with prior lung or heart diseases, and the elderly and children are more likely to be negatively affected by PM exposure (EPA, 2017b). Evidence from a study conducted in 2010 by the State of Alaska Department of Epidemiology revealed a correlation between hospitalizations and PM2.5 episodes in the FNSB. Improved FNSB air quality from a reduction in particulate matter could reduce asthma and cardiovascular induced hospitalizations from PM2.5 episodes during winter months (State of Alaska Department of Epidemiology, 2010).[7]

Due to the unique geography of Fairbanks, the FNSB non-attainment zone is located within an inversion, which is one of the reasons for serious PM2.5 non-attainment. During severe winter weather conditions, colder more dense air sinks down from surrounding hills underneath less dense warm air, trapping cold air in the valley, and a warmer air mass hovers on top of the colder air mass. This weather condition is illustrated by *Figure 2* below.

[7] More information on the State Department of Epidemiology report can be found here: dec.alaska.gov/media/7528/epibulletinfbxpm25hospital.pdf

Figure 2: Weather Inversion



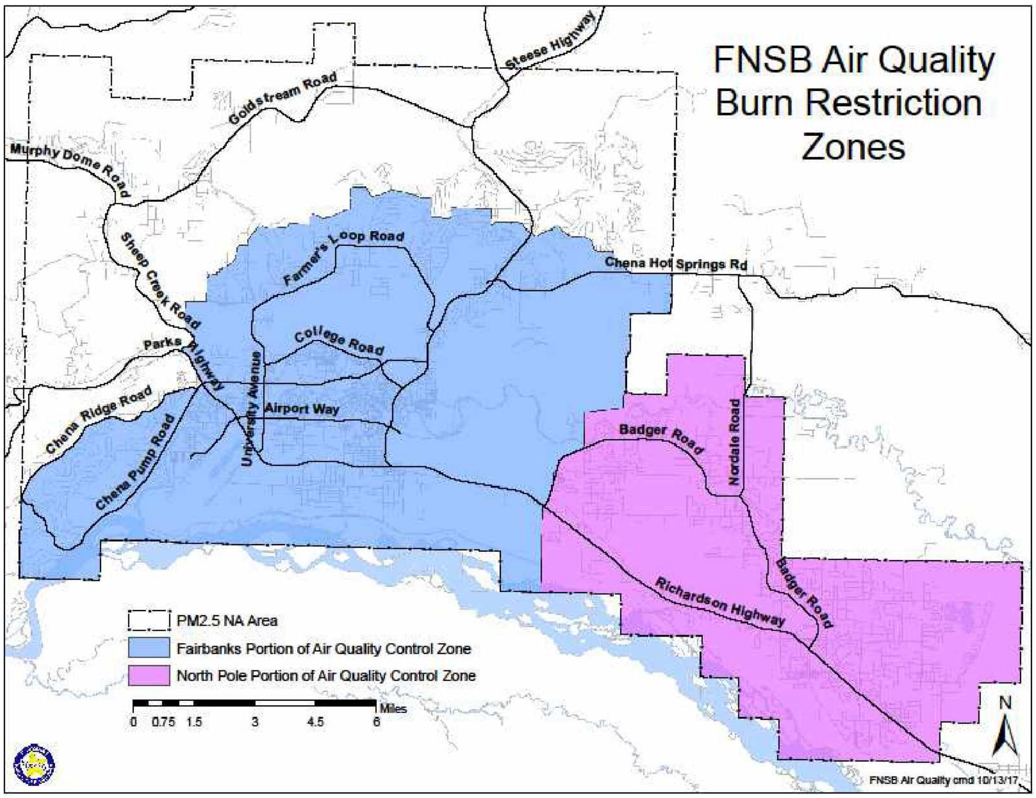
Source: http://health.utah.gov/asthma/airquality/winter.html

The inversion traps pollution down towards residents in the PM2.5 control zone during cold weather episodes. If the severe winter weather episode is prolonged, emissions are continually trapped in the cold, dense air closer to the majority of residents in the FNSB. However, residents that live in the hills surrounding Fairbanks generally live in warmer temperatures above the pollution, and for that reason elevation of the home in feet above sea level is included as a variable in the analysis. It is expected that residents that live above the cold-air inversion in warmer temperatures tend to use less heating energy than those households living in the cold-air inversion.

Below is a map of the Borough's different Air Quality non-attainment boundaries. The dashed line indicates the PM2.5 non-attainment area boundary, which was established by the EPA.

The blue and purple shaded areas combined are the Air Quality Control Zone (AQCZ). The blue shaded area is the Fairbanks portion of the AQCZ, while the purple shaded area is the North Pole portion of the AQCZ.

Figure 3: FNSB Air Quality Control Zone Boundaries



Source: Fairbanks North Star Borough, Air Quality Division Website, (2015)

Concentrations of PM2.5 tend to be higher in the shaded areas of Fairbanks and North Pole AQCZ. It is important to mention that PM2.5 is generally only a concern during winter months (October through March) when strong temperature inversions are frequent and the impacts of pollution increase.

Theoretical Framework[8]

The basis for household energy demand and the PCAIDS model relies on the microeconomic principals of consumer demand theory. Households consume energy by allocating income among energy inputs to obtain the greatest utility from the total expenditure on household heating. Households will choose a combination of residential heating energy to maximize the utility derived from household heating. Like basic utility theory – it is assumed that households partake in preference ordering which can be represented by a utility function; it is assumed that households are rational consumers and that they will determine the most preferred "bundle" of energy resources from other alternatives.

Due to differing preferences, two households with identical observable characteristics (income, size of home, weather locale, appliance type, family size, etc) may demand different bundles of goods, including energy goods (Kristrom, 2008)[9]. Furthermore, it can be concluded that response to price changes may differ between otherwise identical households due to differing household preferences.

Following consumer theory – any increase in consumption of one good while keeping other goods consumption constant increases total utility, while diminishing marginal utility as consumption of energy increases. Estimates of the own-price elasticity of demand for heating oil will be influenced by the presence of an alternate heating source, in this instance a wood stove or wood stove insert. Based on standard economic theory homes without an alternate source of heat will have a more inelastic short-run demand for home heating oil. Conversely, homes with an

[8] This section is based on Bhattracharyya & Timilsina, 2009 and Nicholson & Snyder, 2008

[9] Detailed research by Lutzenheiser (1993) shows that similar households living in similar housing display widely varying energy consumption patterns.

additional source of heat such as wood stove or insert would be expected to be more sensitive to heating oil price changes since they will be able to shift a portion of home heating burden to the other appliance. The estimated cross-price elasticity of wood demand in response to a change in heating oil price measures the increase in wood consumption. It is assumed that wood and oil are substitute goods – or as the price of oil decreases, households tend to increase oil consumption and decrease wood consumption in the face of lower oil prices.

Consider the consumer utility function, where the individual's objective is to maximize utility from *n* goods:

$$Utility\ U = U(X_1, X_2, \ldots, X_n) \qquad (1);$$

Subject to the budget constraint[10]

$$I = P_1X_1 + P_2X_2 + P_nX_n \qquad (2);$$

For maximization of utility subject to the budget constraint, set up the Lagrangian expression

$$L = U(X_1, X_2, X_n) + \lambda(I - P_1X_1 - P_2X_2 - P_nX_n) \qquad (3);$$

Set partial derivatives of L with respect to (X_1, X_2, X_n) equal to zero yields $n+1$ equations representing the necessary conditions for an interior maximum

$$\frac{\partial L}{\partial X_1} = \frac{\partial U}{\partial X_1} - \lambda P_1 = 0 \qquad (4);$$

$$\frac{\partial L}{\partial X_2} = \frac{\partial U}{\partial X_2} - \lambda P_2 = 0 \qquad (5);$$

[10] The budget constraint is written as equality – given assumption of nonsatiation, consumers are assumed to spend all available income (Nicholson and Snyder, 2008)

$$\frac{\partial L}{\partial X_n} = \frac{\partial U}{\partial X_n} - \lambda P_n = 0 \quad (6);$$

$$\frac{\partial L}{\partial \lambda} = I - P_1 X_1 - P_2 X_2 - P_n X_n = 0 \quad (7);$$

The above *n+1* equations can be solved for optimal X_1, X_2, X_n and λ, yielding demand functions in prices and income.

$$X_1 = d_1(P_1, P_2, \dots P_n, I) \quad (8);$$

$$X_2 = d_2(P_1, P_2, \dots P_n, I) \quad (9);$$

Individual demand curves illustrate the relationship between price and quantity of the good purchased, holding all else constant. Household demand functions for a particular energy source (heating oil or wood) can be summed to generate an aggregate market energy demand function. The market demand function is constructed by varying the price of the good while holding all other determinants constant (Bhattracharyya & Timilsina, 2009).

Analytical Framework: PCAIDS Model

The PCAIDS model applies the same logic as the ideal demand system (AIDS) model but incorporates restrictions to make all short-term elasticity values depend on a single aggregate market demand elasticity parameter and market shares of the respective goods. The restrictions imposed ensure the correct signs and magnitudes of required parameters and elasticities (Epstein & Rubinfeld, 2002).The modeling approach used here follows Coloma (2006) who presents a two stage process to deriving own- and cross-price elasticities of demand using the PCAIDS framework. From a policy perspective, short-run elasticities provide better information than longterm elasticities regarding the distributional consequences during a period of time when households are not able to adjust their appliances.

In many instances data limitations make it difficult to estimate the full AIDS model developed by Deaton & Muelbauer (1980). An alternative to the AIDS model is the "proportionally calibrated almost idea demand system" (PCAIDS) model developed by Epstein & Rubinfeld (2002).

The PCAIDS model has fewer data requirements than the typical AIDS model, providing an alternative strategy to estimating demand systems in the presence of imperfect information. The PCAIDS model avoids many of the challenges of the traditional AIDS framework, notably the estimation of a large set of parameters and the potential for low statistical significance, implausible magnitudes, or wrong signs inconsistent with economic theory. PCAIDS relies on a generalized principle of strict proportionality to reduce the number of parameters in the demand model: an increase in price from a single good will result in substitution to other goods in proportion of current market sales. PCAIDS assumes that the share lost as a result of price increase is allocated to other goods in the relative market with respect to their proportional share. By definition of strict proportionality, since the shares must sum to 1 (100%) the model satisfies the adding up constraint.[11]

To estimate the own-price elasticity of demand for oil and cross-price elasticity of demand for wood, two required parameters must be recovered from the models: α_{ii} is represented as the adding-up property of the PCAIDS model which is equal to the summation of the cross-price parameter (Coloma, 2006), and n the aggregate demand elasticity of oil. Following Coloma (2006)

[11] Epstein & Rubinfeld (2002)

using available price data for wood and oil, and expenditure shares of wood and oil, the dependent shares model is estimated for α_{ii}.

$$\frac{S_O \cdot (1-S_O)}{S_W} = -\alpha_i \cdot b_{10} + \alpha_{ii} \cdot \ln\left(\frac{P_O}{P_W}\right) - \alpha_{ii} \cdot b_{1\gamma} \cdot \gamma \qquad (10);$$

$$\frac{S_W \cdot (1-S_W)}{S_0} = -a_i \cdot b_{10} + \alpha_{jj} \cdot \ln\left(\frac{P_W}{P_O}\right) - \alpha_{jj} \cdot b_{1\gamma} \cdot \gamma \qquad (11);$$

Where S_O is the oil share and S_w is the wood share expenditure for a household. $ln\left(\frac{P_O}{P_W}\right)$ is the log of relative price ratio of oil and wood per million of BTU (mmBTU). $ln\left(\frac{P_W}{P_O}\right)$ is the log of the relative price ratio of wood and oil respectively in mmBTUs. Parameter α_{ii} describes the relative spending behavior of price-taking buyers and is needed to calculate both own and cross-price elasticities. Parameter α_{jj}, is recovered as the coefficient of $ln\left(\frac{P_W}{P_O}\right)$.

In the second stage of the model, the household heating demand equation is estimated to determine aggregate demand elasticity (n):

$$\ln(Q) = C_0 + n \cdot \ln(P_A) + C_\gamma \cdot \gamma \qquad (12);$$

Where Q is the level of mmBTU consumption for the household, $ln(P_A)$ is a natural log of weighted average price per mmBTU for wood and oil, and C represents the estimated coefficients. The parameter n is the coefficient of $ln(P_A)$ which should be negative and represents the market average own-price elasticity of home heating fuels. Recovered parameters of n and α_{ii} can be used to calculate α_{ij} and the own-price (n_{own}) and cross-price (n_{cross}), elasticities of demand for oil and wood respectively.

The cross-price elasticity of demand – α_{ij} and α_{jj} – is calculated with respect to the expenditure shares, and the α_{ii} parameter estimated in equation (1). Estimating the α_{ij} cross-price parameters has the following relationship with α_{jj} from equation (2):

$$\alpha_{ij} = \frac{-S_O}{(1-S_W)} \cdot \alpha_{jj} \qquad (13);$$

α_{ij} is then used to estimate n_{cross}, the cross-price elasticity of demand for wood with respect to a change in oil price. Using the n and α_{ii} parameters, the own- and cross-price elasticity be calculated directly:

$$n_{own} = -1 + \frac{\alpha_{ii}}{S_O} + S_O \cdot (n+1) \qquad (14);$$

$$n_{cross} = \frac{\alpha_{ij}}{S_O} + S_W \cdot (n+1) \qquad (15);$$

Data

Residential energy demand is driven by numerous factors such as energy prices, size of the home, number of household members, household income, weather (heating degree days), energy efficiency, and year the home was built. Empirical studies show household size is a positive and significant parameter that effects households demand for residential energy (Schuler, Weber, & Fahl, 2000; Song et al, 2012). A demand for space heating study of 551 Norwegian households supports the assumption that home size positively effects energy consumption. The same study found that the age of the home has a direct relationship with energy consumption, i.e. the older the home, the higher the energy consumption (Nesbakken, 2000). Annual heating degree days are included to capture differences in energy preferences, and control for local weather effects on household energy consumption

Energy prices are shown to be an important factor for determining household energy consumption (Isaskson, 1983; Scott, 1980). The price of heating oil does not only affect household level energy consumption, but also impacts the household's choice towards adopting alternative heating systems and fuel combinations (Krumm, 1982). Moreover, a household's ability to respond to change in fuel oil price increases by utilizing supplementary heating appliances such as wood stoves, fireplaces, or portable heaters (Reilly & Shankle, 1988). Empirical analysis supports the negative relationship between energy consumption and energy price (Wu, Lampietti & Meyer, 2004).

To estimate own- and cross-price elasticities, the 2016 Home Heating Postcard Survey was be analyzed. The 2016 Home Heating Postcard Survey was conducted by ADEC and consisted of questions which asked respondents about their household's annual use of home heating oil and wood (ADEC, 2016). A total of 1,401 postcards were mailed to all respondents in the 2014 and 2015 Fairbanks Home Heating Telephone Surveys between 2011-2015 (ADEC, 2015). Respondents were provided pre-printed 2014 or 2015 device/usage data for each individual respondent or the households "first observation". A total of 271 postcards were returned over the ensuing three months, reflecting a return rate of just under 20% (Sierra Research White Paper, 2016).

It is important to note that many households collect wood for use. It is assumed that the time and input costs associated with the collection of wood are commensurate with the market price used in the analysis. The dependent shares are modeled as a function of the relative fuel price ratio and other factors (Y), which include: the square footage of the home, age of the home in years, and the elevation at the housing location. A year level fixed effect controls for the annual variability due to changes in heating degree days. As energy efficiency of individual household appliances was not captured in the postcard survey data used, it is important to note that this study assumes a constant appliance efficiency. The following table displays the variable name and descriptions used in the analysis.

Table 4: Variable Descriptions

Variables	Description	Mean
SHARE_O	Relative share of oil and wood expenditures	0.55
SHARE_W	Relative share of wood and oil expenditures	0.19
AGG_Q	Quantity of household oil and wood consumption in mmBTU	126.60
BTU_OIL	The relative price ratio of oil and wood per mmBTU	1.61
BTU_WOOD	The relative price ratio of wood and oil per mmBTU, used in the wood dependent shares model	0.63
P_A	The weighted average mmBTU prices of firewood and heating oil	19.28
YEAR	Study year dummy variable 0 = 2015, 1 = 2016	
DV	Dummy variable indicating 0 = no direct vent appliance is used in the home, 1 = direct vent appliance is used in the home	0.175
COIL	Dummy variable indicating 0 = no central oil appliance is used in the home, 1 = central oil appliance is used in the home	0.83
WC	Dummy variable indicating whether the household bought or collected wood 0 = the household bought wood, 1 = the household collected their own wood	0.38
SIZE	Size of the home in square feet	1977.65
ELEVATION	The feet above sea level where the home is located	616.48
AGE	Age of the home in years since the home was build	26.95

Following the initial uses of the first household observation in the Home Heating Telephone Survey, the 2016 Home Heating Postcard Survey is a balanced panel dataset consisting of 271 responding households. Data from the first observation from the telephone survey and 2016 postcard survey were paired by household. ADEC performed a series of calculations to validate the data for each household. ADEC calculated fuel use data by device from each survey "point" (first observation vs. 2016 postcard) which were then translated into estimates of winter heating energy use, measured in mmBTUs. All models are estimated using the 231 household responses determined to be valid by ADEC. Further information regarding the validation process conducted by ADEC, Inc can be found in the Appendix.

The following table is the related summary statistics for the Fairbanks Home Heating Postcard Survey.

Table 5: Market Prices, Expenditures, and Shares

Year	Oil Price	Wood Price	Oil Price (mmBTU)	Wood Price (mmBTU)	HH Expenditures	Oil Shares	Wood Shares
FO	3.38	275.51	24.87	13.53	$2,900 ($2.985)	0.71 (0.36)	0.29 (0.36)
2016	2.39	266.99	17.70	13.11	$2,600 ($1,778)	0.76 (0.30)	0.24 (0.30)
Total	2.87	271.25	21.04	13.32	$2,750 ($2459)	0.74 (0.33)	0.26 (0.33)

Note: Standard deviations in parentheses
Survey: Fairbanks Home Heating Postcard Survey

Table 6 presents the change in market prices for wood and oil from the first observation to 2016 in gallons and cords of wood as well as in price per mmBTU by fuel type.[12] The change from $275.51 to $266.99 represents a 3.10% decrease in the market price for a cord of wood. The

[12] Firewood and oil prices found from the Alaska Energy Data Gateway, 2018

average change from $3.38 to $2.39 represents a 28.66% decrease in the market price for heating oil. Oil shares increase from 71% to 76% of household heating expenditures between the two time periods - this represents a 7% increase in expenditures on heating oil. Wood shares decrease from 29% to 24% of household heating expenditures, this represents a 17% decrease in household expenditures on firewood between the two time periods. The increase in heating oil expenditure shares of approximately 5% - a decrease in wood expenditures shares of 5% - indicates that as the price of heating oil relative to wood becomes cheaper, households tend to substitute towards using more heating oil. Overall expenditures for households decreased from $2,900 to $2,600 annually representing a 10% decrease in annual household heating expenditures.

Table 6: Total Household Energy consumption in mmBTU and Heating Degree Days

Year	Energy consumption (mmBTU)	Heating degree days
2014/15	134.42 (111.91)	10,199
2016	119.14 (78.75)	9,735
Total	12.78 (96.97)	9,967

Note: Standard deviations in parentheses
Survey: Fairbanks Home Heating Postcard Survey

Table 6 displays household change in total energy use in mmBTU, and heating degree days from 2015 to 2016. The change from 138.81 mmBTU's to 118.1 mmBTU's represents a 15% decrease in annual energy use from the first observation to 2016. The change from 10,119 to 9,735 heating degree days represents a 3.75% decrease in annual heating degree days in the FNSB.

The household share of expenditures devoted to firewood and heating oil, as well the total share of expenditures is estimated for the average household.

Using the expenditure shares, the equation (5) is estimated as follows:

$$SHARE\_O = \beta_0 + \beta_1 BTU\_OIL \quad + \beta_2 YEAR + \beta_3 DV + \beta_4 COIL + \beta_5 WC + \beta_6 LN(SIZE) + \beta_7 LN(ELEVATION) + \beta_8 AGE + U \qquad (16);$$

To estimate the cross-price effect of wood with respect to a change in oil, equation (2) is estimated using:

$$SHARE\_W = \beta_0 + \beta_1 BTU\_WOOD + \beta_2 YEAR + \beta_3 DV + \beta_4 COIL + \beta_5 WC + \beta_6 LN(SIZE) + \beta_7 LN(ELEVATION) + \beta_8 AGE + U \qquad (17);$$

The aggregate market demand model is estimated using equation (3)

$$LN(AGG_Q) = \beta_0 + \beta_1 LN(P_A) + \beta_2 YEAR + \beta_3 DV + \beta_4 COIL + \beta_5 WC + \beta_6 LN(SIZE) + \beta_7 ELEVATION + \beta_7 AGE + U \qquad (18);$$

Analysis and Results

Tables 7 and *8* below present regression results from the models.

Table 7: Dependent Shares Models

VARIABLES	(1) SHARES_OIL	(2) SHARES_WOOD
PRICE_RATIO[13]	0.076 (0.067)	0.052 (0.096)
YEAR	0.07 (0.051)	0.012 (0.029)
DV	0.164***(0.051)	-0.007 (0.043)
COIL	0.484***(0.052)	-0.257*** (0.051)
WC	-0.044 (0.035)	0.210*** (0.025)
LN(SIZE)	-0.093* (0.054)	0.015 (0.028)
LN(ELEVATION)	-0.027 (0.048)	0.040 (0.036)
AGE	-0.0012 (0.0014)	-0.0012 (0.0008)
Constant	0.942* (0.540)	-0.028 (0.290)
Observations	244	407
Adj. R-squared	0.2759	0.2836

Note: Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Two hundred and forty-four observations are analyzed in the *DEPSHARES_OIL* model, if a household does not have an expenditure share on wood the dependent share would be undefined (missing). The dependent shares model is estimated using the 244 observations for households which reported having both a wood and oil appliance.

Four hundred and seven observations are analyzed in the wood dependent shares model, again the discrepancy between the number of valid households and the number of analyzed households is due to the way the wood dependent shares model is calculated (equation 15). If a household has only wood and no oil appliance, there would be no dependent shares calculated for

[13] The PRICE_RATIO is flipped between the two separate models, see equations 14 and 15

that household given the denominator (oil share) would be undefined which would generate a missing wood dependent share observation for that household.[14]

Table 8: Aggregate Demand Model

VARIABLES	(3) LN(AGG_Q)
$LN(P_A)$	-0.246** (0.116)
YEAR	-0.235*** (0.054)
DV	0.133 (0.085)
COIL	0.511*** (0.085)
WC	0.129*** (0.043)
LN(SIZE)	0.448*** (0.052)
LN(ELEVATION)	-0.121* (0.065)
AGE	0.0002 (0.0014)
Constant	2.46*** (0.569)
Observations	434
Adj. R-squared	0.3838

Note: Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Four hundred and thirty-four observations are analyzed in the aggregate demand model, the model uses all observations deemed valid in the dataset that have wood and oil appliances. Observations reporting other energy uses such as coal or wood pellets were not included in the models. Due to the nature of the PCAIDS model, it is important to note that the own-price elasticity

[14] The odd number of households analyzed in the dependent shares wood model is due to some households reporting oil use in one time period and reporting no oil use in the other time period. Therefore, the household would have a value for wood dependent shares in one time period, but not in the other.

of homes with oil appliances are the same given the oil share and α_{ii} parameter is constant across all observations with heating oil only appliances.

All estimated coefficients presented in the models have the expected signs, insignificant variables were not omitted from the model.[15] All models were tested for omitted variable bias using the Ramsey RESET test, all models rejected the null in favor of the alternative that the models have no omitted variables. *Table 9* displays the estimated mean own- and cross-price elasticities of demand for wood and heating oil.

Table 9: Mean Estimates of Own- and Cross-Price Elasticity Estimates for Heating Oil and Wood

	Linear Regression
Own-Price Oil (Mean)	-0.259
	[-0.272, -0.246]
Cross-Price Wood (Mean)	0.198
	[0.171, 0.234]

Note: Confidence intervals are in brackets below.

Confidence intervals were constructed for the means of the own- and cross-price elasticities at 95% confidence level, it can be inferred from a statistically significant aggregate demand elasticity coefficient, as well as the confidence intervals do not contain zero in either the own- or cross-price elasticity of demand, that both elasticity measurements can be assumed to be statistically significant. *Table 10* displays the estimated median own- and cross-price elasticities of demand for wood and heating oil.

[15] Models were also estimated using fixed effect, robust regression, and a linear regression absorbing by year, regression techniques, however the models yielded similar results to OLS regressions, meaning the heterogeneity of households is controlled for in the OLS regression.

Table 10: Median Estimates of Own- and Cross-Price Elasticity Estimates for Heating Oil and Wood

	Linear Regression
Own-Price Oil (Median)	-0.198
Cross-Price Wood (Median)	0.151

The conclusions of this analysis are as follows: energy consumption is inelastic, and the demand curve is downward sloping given the negative weighted energy price variable for the Fairbanks residential heating data analyzed. Findings indicate that energy demand elasticity is -0.246. Or for every 1% increase in the weighted price, there is a -0.246% decrease in reported household energy consumption. Household size is statistically significant at the 0.01 level and has the expected positive sign in the aggregate demand model. A 1% increase in household size increases residential energy demand by 0.443% this result is in line with (Nesbakken, 2000; Sardianou, 2007).

Elevation of the home is statistically significant at the 0.1 level and has the expected sign in the demand model. A 1% increase in elevation leads to a -0.12% decrease in energy demand. Due to warmer temperatures at higher elevations around Fairbanks, homes above the cold weather inversion are expected to use slightly less heat. Age of the home is statistically insignificant, due to the lack of home energy efficiency data, age of home is used as a proxy in the models. However, the age of the home does not take into consideration that some older homes may have upgraded to more efficient wood stoves or central oil boilers.

In the *SHARES_OIL* model, dummy variables *DV* and *COIL* are statistically significant at the 0.01 level. Households with a DV appliance on average have higher oil share expenditures by 0.164 than those households without a DV appliance. Households with a central oil appliance on average have higher oil share expenditures of 0.484 than those households without a central oil appliance.

In the aggregate demand model, those with a central oil appliance have 66.7% higher BTU consumption than those households that do not. Those households that reported collecting their own wood had higher had 13.8% higher mmBTU consumption than those that bought their own wood. Results indicate that households that report collecting their own wood, instead of purchasing have more elastic demand for heating oil. Therefore, these households are more sensitive to changes in heating oil prices, which is consistent with the expected results. Additionally, households that collect their own wood have a higher cross-price elasticity of wood, indicating that as heating oil prices increase, households that collect wood will substitute more wood for heating oil than households that purchase wood.

In the *DEPSHARES_WOOD* model dummy variables *COIL* and *WC* are statistically significant at the 0.01 level. Households with a central oil appliance are expected to a have lower expenditure shares of 0.257 on wood than those households without central oil appliances. Households who cut their own wood are expected to have higher wood expenditure shares of 0.21 than houses that purchase wood. The year variable representing annual heating degree days, also has the expected sign due to the large decrease in annual heating degree days from the first observation to 2016. In 2016, there was 26.5% less energy demand due warmer local weather conditions. *Table 11* displays the own- and cross-price elasticity values for households that collect wood and households that purchase wood.

Table 11: Own- and Cross-price elasticity of Households Collecting vs. Purchasing Wood

	Collect Wood	Purchase Wood
Own-Price Oil (Mean)	-0.307	-0.229
Cross-Price Wood (Mean)	0.210	0.185

The assumption is made that the time value of those households that cut their own wood is equal to the market price, which also indicates that households that cut their own wood instead of purchase will have a higher cross-price elasticity of demand. While the assumption that, the time-value of money and market price for those that collect wood vs. buying wood is the same, was required for statistical analysis – results indicate that households that collect wood have a higher consumption than those that purchase meaning this assumption is not necessarily true. This suggests that market price is higher than the time-value of money for households that collect wood instead of purchase wood.

The average own-price elasticity with respect to heating oil is inelastic at a value of -0.259. *Table 12* displays other empirical results on own-price elasticity of demand for residential heating oil. Average heating oil elasticities range from -0.15 to -0.47. The wide range of own-price elasticity measurements is due to difference in specification of the models, location, household preferences in that location, and time-period of the dataset.

Table 12: Oil Price Elasticity Estimates in Literature

Author(s)	Own-price elasticity of Oil
W.T. Win et al, (1985)	-0.167 to -0.19
Liu, (2004)	-0.143
Labandiera, Labeaga, & Lopez-Otero, (2011)	-0.242 to -0.259
Galvin & Blank-Sunikka (2012)	-0.39 to -0.47
Madlener, Bernstein & Gonzalez (2011)	-0.15 to -0.34

Cross-price elasticity of wood is estimated to be 0.198, this indicates wood and oil are substitutes. Although many analyses provide elasticity estimates for heating oil (Krumm, 1982; W.T. Win et al., 1985; Liu, 2004; Labandiera, Labeaga, & Lopez-Otero, 2011; Madlener, Bernstein, & Gonzalez, 2011) there are few academically reviewed articles analyzing the own- and cross-price elasticities with respect to wood or wood burning appliances. Song et al., (2012) is one of the few peer-reviewed articles examining the cross-price effects of wood with respect to changes in non-wood energy prices. Song et al, finds that that for every 1% increase in non-wood energy prices is predicted to induce a 1.55% increase in firewood energy consumption. Interestingly, results indicate that non-wood energy prices have a larger marginal effect on household wood energy consumption than household income. As expected, public policies that increase costs of non-wood energy may promote the use of residential wood energy. Pertaining to estimates in this study, a 1% increase in oil-prices will increase wood consumption by 0.198%.

Further Consideration: Monte Carlo Simulation

For this analysis, the objective of the Monte Carlo application is to use the own- and cross-price elasticity estimates to help predict the expected change in household heating expenditure given a range of potential heating oil price increases. If a mandated switch to ULS or HS No. 1 were to occur, Monte Carlo is a useful tool for understanding how changes in price are predicted to increase heating oil and wood costs and consumption for FNSB households. Additionally, this measure not only provides an application of, but a means to perform a sensitivity analysis of estimated results.

Monte Carlo Simulations for residential energy demand has been used in several journal articles (McQueen, Hyland, & Watson, 2004; Fell, Li, & Paul, 2010; He et al. 2012). The Monte Carlo Simulation uses statistical sampling to obtain a probabilistic approximation to the solution of a model or an equation by simulating 5000 predicted observations based on inputs of a range of estimates. In other words, it approximates the output of a model through the repetitive and random application of the model's framework. Through this process, the Monte Carlo Simulation tells us, based on a range of estimates, how probable the resulting outcomes are and can include a mix of point estimates and distributions for the input parameters. The inputs used in the Monte Carlo Simulation are shown in *Table 13*.

Table 13: Summary of Monte Carlo Inputs

Inputs			
Variable	**Min**	**Max**	**Mean**
ULS Differential	0.2	0.4	0.34
Oil Use (Gallons)	45	3500	792
Wood Use (Cords)	0.05	15	3.6
Own-Price Elasticity of Demand	0.198	0.259	0.228
Cross-Price Elasticity of Demand	0.171	0.234	0.198
Current Fuel Price			
$3.20			
Current Wood Price			
$232.16			

The change in expenditure based on the Monte Carlo Simulation is calculated as so:

$$\Delta Exp = \left(\left(-Ed * \frac{Q_O}{P}\right) * Differential + Q_O\right) * \left((P + Differential) - (Q_O * P)\right) \qquad (19);$$

Where *Ed* is the own-price elasticity of demand for heating oil, *Qo* represents the consumption of heating oil in gallons, *Differential* is the additional premium paid as a result of higher heating, and *P* is the price of heating oil per gallon.

Next, to derive a change in quantity:

$$Ed = \frac{\%\Delta Q}{\%\Delta P} = \frac{\frac{(Q_2 - Q_1)}{Q_1}}{\frac{(P_2 - P_1)}{P_1}} \qquad (20);$$

Where *Q2* is the new quantity demanded after the price change, *Q1* is the original quantity demanded at the original price, *P2* is the price of heating oil plus the premium, and *P1* is the original price of heating oil.

Then, simply solve for the change in quantity by solving:

$$\Delta Q = \frac{(Ed*(P_2 - P_1))}{P_1} * Q_1 \quad (21);$$

Tables 14 and 15 present the estimated change in use and expenditure based on the Monte Carlo inputs.[16]

Table 14: Change in Household Energy Consumption

Change in Consumption	Mean	Median	Min	Max
Change in Oil Consumption (gallons)	(27.71)	(25.44)	(84.45)	(1.1)
Change in Wood Consumption (cords)	0.12	0.10	0.0002	0.31
Change in Net Consumption (mmBTU)	(1.68)	(1.46)	(10.25)	4.46

Based on the results of the Monte Carlo, the average change in annual household oil consumption is a reduction of approximately 28 gallons. The average change in annual household wood consumption is an increase of 0.12 cords. These results confirm the results of the statistical analysis that heating oil and wood are substitutes – in the face of higher heating oil prices for households, there will be a decrease in the consumption of heating oil and an increase in the

[16] Current Price for HS No. 1 from the Alaska Energy Data Gateway, October 2018

consumption of wood. While net consumption of energy will decrease overall, given the higher levels of PM2.5 per mmBTU of wood than oil, policies resulting in higher heating oil prices in an attempt to lower PM2.5 emissions could serve counter to goals to reduce PM2.5 in the FNSB. Though *Table 15* below shows changes in expenditures for household heating energy.

Table 15: Change in Household Energy Expenditure ($)

Change in Expenditure ($)	Mean	Median	Min	Max
Change in Oil Expenditure	294.62	270.55	12.70	809.84
Change in Wood Expenditure	23.87	22.10	0.49	71.22
Change in Net Expenditure	318.49	292.65	13.19	881.06

Based on the results of the Monte Carlo, the average change in annual household oil expenditure is $294.62. The average change in annual household wood expenditure is $23.87, and the change in net expenditure is approximately $318.49. When analyzed in conjunction with changes in consumption from *Table 13,* though households are expected to decrease consumption of oil by an average of 28 gallons, there is an overall increase in the average household expenditures on oil given the higher heating oil price premium. Though there is a net decrease in overall consumption of both wood and heating oil energy, households are expected to spend an additional $318.49 annually for household heating energy. Given annual expenditures of $2750 on household heating, this increase of $318.49 represents an increase of 11.5%.

Figure 4: Distribution of Change in Net Household Energy Expenditure ($)

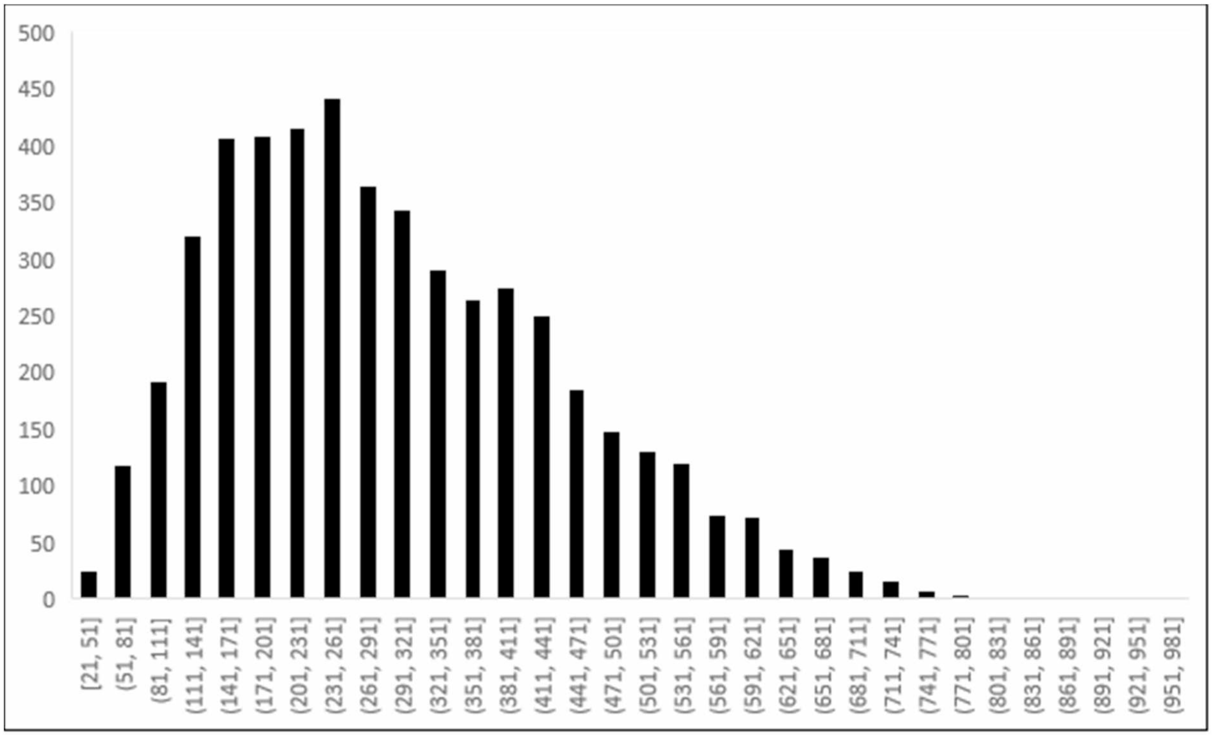


Figure 4 presents the triangular distribution of simulated expenditure increases based on the range of HS No. 1 price increases. Given the leftward skew distribution of the data, 94.6% of simulated households are predicted to increase their net change in expenditure by approximately $100 or more annually, though all households in the simulated were predicted to increase their expenditures overall.

Figure 5: Distribution of Net Change in Household Energy Consumption (mmBTU)

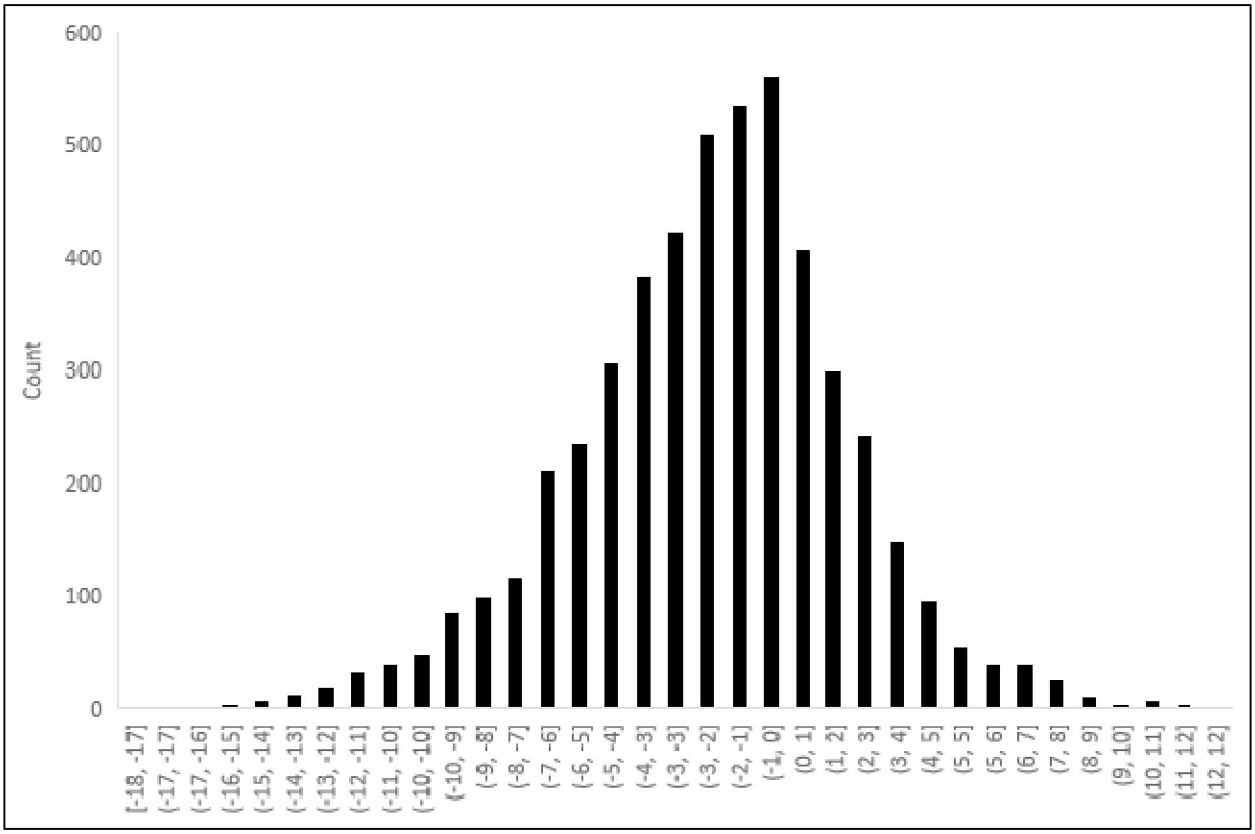


Figure 5 presents the triangular distribution of the change in net consumption given an increase in heating oil prices. Approximately 71% of households are predicted to decrease overall net energy consumption, leaving approximately 29% of households with a predicted increase in overall net energy consumption. 83.5% of households are predicted to decrease oil consumption by 15 (2.025 mmBTU) gallons or more. 57.3% of households are predicted to increase wood consumption by 0.1 cords (2.01 mmBTU) or more.

A Monte Carlo simulation was run for a hypothetical switch from HS No. 2 to HS No. 1, however the changes in expenditure and consumption of both wood and oil did not result in a significant difference given the small differential between HS No. 1 and HS No. 2.[17]

Discussion

Evidence suggests households that pay higher heating oil prices tend to consume additional of wood energy. At a cross-price elasticity of 0.198 with respect to heating oil prices suggests substitutability between wood and heating oil. Evidence from the Monte Carlo suggests that in the face of higher oil prices, households with wood and oil appliances may reduce total energy consumption but will tend to burn more total wood energy and less oil energy. Ericsson et al., (2004) suggests increasing taxes on fossil fuels as a policy instrument would promote the use of wood energy, as it would increase cost competitiveness of wood energy in relation to other non-wood energy.

Aguilar & Saunders, (2011) suggests a downward trend in residential wood energy consumption associated with when houses were built, proposing that newly built houses use less wood energy. Song et al., (2012) states residents of newer houses built after 1990 use substantially less wood energy than older homes build before 1990. This could be associated with the fact that residents of newer houses may have higher income than residents living in older houses could be associated – which could also explain lower wood use.

An effective policy tool for reducing the consumption of wood energy and thereby reducing PM2.5 emissions could be preferential tax treatment for households installing higher efficiency wood-based burning systems given the substitutability between wood and oil energy. Additionally,

[17] HS No. 1 and HS No. 2 differential is $7 cents/gallon (ADEC, 2019a)

creating incentives for FNSB households to change-out older heating oil boilers could prove effective without increasing oil prices. Mandatory upgrades for households with wood-stoves out of compliance with Alaska Department of Environmental Conservation ADEC regulations could be implemented to force efficiency upgrades to EPA certified clean outdoor wood burner devices.

Additionally, tightening regulations for wood burners in relation to the dryness and cleanness of wood could serve to use market forces to increase the price of wood-energy in relation to heating oil energy thereby reducing wood-energy consumption.[18] As of November 23rd, 2017, those households caught out of compliance were served with a letter and the potential – if caught out of compliance again – to be served with a $500.00 fine.[19] Enforcing heftier fines or court actions by ADEC for wood-burners caught out of compliance could serve to discourage non-compliant wood burning during air quality episodes. Heightening education efforts surrounding PM2.5 emissions and its relationship to wood-burning and impact on health and the environment could prove effective in reducing wood-energy pollution.

Nobel Prize winning behavioral economist's Richard Thaler and Cass Sunstein in their book "*Nudge*" have this to say with regards to remedying unwanted behavior regarding pollution and environmental malaise:

"One of the problems that contributes to excessive pollution is that people do not get feedback on the environmental consequences of their actions. If your use of energy produces air

[18] Though there is not sufficient data to postulate on the level of reduction of wood burning would take place with an increase in wood price in this analysis - consistent with economic theory - lowering the cost of wood energy for households will reduce prices of wood energy relative to prices of heating oil would prompt higher wood energy consumption (Hardie and Hassan, 1986; Skog and Watterson, 1984; Song et al, 2012).

[19] https://dec.alaska.gov/air/anpms/communities/fbks-pm2-5-curtail-details/

pollution, you are unlikely to know or appreciate that fact on a continuing basis…. and are unlikely to think about all the personal and social costs moment-by-moment, or even day-by-day"

Given the political difficulty of dealing with environmental problems by aligning government and public incentives, it can prove challenging to unite on a solution. If voters are already incurring high home heating expenses, it could prove difficult to agree on a solution that increases the overall price of home heating. Thaler & Sunstein (2009) suggest that in conjunction with aligning incentives through tax-based approaches, using social incentives can prove effective and more politically palatable. Thaler and Sunstein explore efforts of Southern California to encourage individuals to conserve energy – while findings indicate that emails and text messages reminding individuals to conserve energy are ineffective, giving consumers a visual tool as a way to monitor their energy use has proven effective.

Thaler and Sunstein note the underlying issue of energy consumption is the fact that it is invisible – households and individuals are unaware when using a significant amount. The Wattson Kyoto DIY energy device allows users to visualize the amount of energy being used.[20] Ueno et al., (2005) utilized an online energy consumption information system to provide visual feedback to households regarding energy consumption. Estimates indicate that installation lead to a 9% reduction in energy consumption.

Additionally, allowing households to upload their energy consumption to an online community forum or other comparable web-sites that present their improvements compared to other households in the community, if FNSB households choose to opt-in, this could create a cascading social effect of the case for decreasing energy consumption. Peterson et al., (2007) used

[20] http://diykyoto.com/uk/aboutus/wattson-classic

an energy-based competition among student dormitories. During the 2-weeks of observations, the overall reduction in energy use totaled 32%, those dormitories that received weekly feedback from meter readings on energy use reduced energy use by 31%, and dormitories that received web-based real-time feedback reduced energy use by 55%. Thaler proposes that by making energy use visible and providing feedback, we can give a social “nudge” to consumers to reduce energy consumption without mandating reductions.

To address complaints of ambient air quality issues from cruise ships in Juneau, ADEC is conducting studies using a similar PM2.5 feedback device the PurpleAir air quality sensor.[21] The PurpleAir is an inexpensive device to measure PM and other air pollution that uploads air quality measures to the internet approximately every 80 seconds and are displayed on a map. This allows members of the public and other entities to view in real-time pollution measures.

An implementation of this type of social program in the FNSB could prove effective in conjunction with a tax-based approach. Having a device similar to the Wattson Kyoto DIY, or the PurpleAir installed to allow FNSB households to visualize their energy consumption could help households, not just lower wood energy consumption, but total energy consumption, thereby decreasing overall PM2.5 emissions without the political difficulty of tax-based solutions.

Conclusion and Future Research

This study conducted an analysis to estimate the own- and cross-price elasticities of heating oil and wood respectively. Unlike previous studies, this study estimates the cross-price elasticity of wood for application to local policy provisions for wood burning given the need to improve local air quality. Price elasticity estimates of energy demand are imperative to understanding how

[21] https://www.purpleair.com/sensors

changes in energy prices may impact energy consumption at the household level. This could result in an increase in the amount of PM2.5 given the potential to use more fuel and or shift to dirtier fuel sources. Estimates indicate an inelastic demand for oil – a 1% increase in the price of heating oil will decrease consumption of heating oil by 0.259%. Estimates indicate wood and heating oil are substitutes - a 1% increase in heating oil is predicted to increase wood energy consumption by 0.232%. This analysis is one of the few to estimate the cross-price elasticity of wood consumption with respect to a change of price in oil using the PCAIDS method.

Based on the results of the Monte Carlo, given an increase in the price of heating oil of between 20 cents/gallon and 40 cents/gallon, approximately 71% of households are predicted to decrease overall net energy consumption, leaving approximately 29% of households with a predicted increase in overall net energy consumption. 83.5% of households are predicted to decrease oil consumption by 15 (2.025 mmBTU) gallons or more. 57.3% if households are predicted to increase wood consumption by 0.1 cords (2.01 mmBTU) or more. Additionally, average increase in annual household expenditure of $294.62 for oil and $23.87for wood. Resulting in a total average annual household expenditure increase of $318.49. Approximately, 94.6% of simulated households are predicted to increase their net change in expenditure by approximately $100 or more annually.

A few limitations should be mentioned. First, because the share equations were estimated separately, symmetry restrictions were not imposed on the demand system. Second, due to lack of time dimension in the data, the models may not capture increases in household efficiencies via the new installation of wood stoves or boilers. Finally, it was not possible to accurately estimate the own-price elasticity of wood with respect to wood use, this is due to a lack of accurate wood price data - many households in Fairbanks report collecting their own wood instead purchasing.

Studies surrounding the energy efficiency of FNSB homes, home-heating preferences, and alternate ways to help FNSB homes voluntarily reduce home heating consumption would serve to complement the findings of this paper. While it is not in the scope of this analysis, using the quadratic almost ideal demand system (QUAIDS) model to estimate separate elasticities for homes with heating oil appliances only would also serve to complement the findings in this analysis

Results of this analysis allow policy makers to identify the sensitivity level of wood consumption to changes in oil prices. Given the substitutability between residential wood and heating oil suggests that implementing public policies that increase the cost of heating oil may promote the consumption of residential wood energy, which could aggravate the air quality issue in the FNSB. The relationship between home heating and FNSB households given the climate and geographic location of Fairbanks makes the local air quality situation unique, however research and evidence from FNSB household heating data can improve the discussion of potential policy solutions.

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Appendix

To ensure the validity of the household responses, households energy use (in mmBTUs) was examined compared the results based on the 2015 data point and that from the 2016 postcard survey. If the energy use from one survey was dramatically different from the other, both data points for the household were deemed invalid. Sierra Research utilized a validation threshold of a ±75% change in energy use to validate or reject the data for each household. Through the validation process, 38 out of the 271 respondents were deemed "invalid." Sierra Research indicates it chose the validation level to account for the combination of variations due to reporting precision of wood use, year-to-year differences in winter severity, and effects of differences in net heating efficiencies across the key devices.