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Factors affecting wood energy consumption by U.S. households

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ABSTRACT

About 23% of energy derived from woody sources in the U.S. was consumed by households, of which 70% was used by households in rural areas in 2005. We investigated factors affecting household-level wood energy consumption in the four continental U.S. regions using data from the U.S. Residential Energy Consumption Survey. To account for a large number of zero observations (i.e., households that do not burn wood), left-censored Tobit models were estimated. Urban/rural location is a key determinant of level of household wood energy consumption. Wood energy consumption elasticity with respect to non-wood energy price changes was 1.55 at the U.S. level, and a much higher 2.30 among rural households. While household wood energy consumption was affected primarily by non-wood energy price in rural areas, it was influenced mainly by household size and level of income in urban areas. Elasticity of wood energy consumption with respect to income can be positive or negative depending on household urban/rural location, region and income level. Newer houses were found to use less wood energy than older ones, and greater urbanization was found to have negative effect on wood energy use. Our findings suggest that policies reducing relative wood energy cost or increasing non-wood energy prices in the residential sector will result in greater wood energy consumption in the U.S. The effect of policies may vary by region and are likely to be more effective in U.S. rural areas and in the U.S. Midwest in particular.

1. Introduction

Wood remains a primary source of renewable energy in the U.S. Energy derived from woody materials, henceforth termed *wood energy*, totaled 2157 PJ (2044 trillion Btu), accounting for about 28% of the renewable energy used in the U.S. in 2008 (U.S. Energy Information Administration, EIA, 2010). The potential annual supply of wood biomass for energy production was estimated to meet up to 6% of U.S. national energy demand (Perlack et al., 2005). About 23% of total U.S. wood energy was consumed by households (EIA, 2010). Residential wood energy has been mainly used for heating purposes and competes with other home heating energies, such as natural gas, electricity, and petroleum products (Hardie and Hassan, 1986; Howard and Westby, 2009; Skog and Watterson, 1984).

The share of wood energy in the U.S. residential sector has experienced a sharp decline over the last 50 years. Wood energy accounted for 23% of total U.S. residential energy in 1945 and only 4% by 1973 (U.S. EIA, 2009a). After a decade-long growth in U.S. household wood energy consumption following the 1973 oil crisis, its market share dropped back to 4% by 1997 and has remained at this level since then (Aguilar et al., 2011; EIA, 2010).

There are three main platforms to generate energy from wood: direct combustion for heating by final users such as mills, households, schools, stores, factories, and public buildings; electricity generation at power plants; and liquid biofuel production. Currently wood energy in the U.S. is primarily used in direct heating and electricity generation, most of it by the wood products industry (about 68%) that utilizes pulping liquors and mill residues (EIA, 2010). Although traditional home fireplaces have a low heat conversion efficiency, newly-installed residential heating systems commonly have efficiency rates higher than 65% which is close to levels observed in combined heating and power (CHP) plants. About two-thirds of existing power plants using biomass are co-firing power plants whose average electricity conversion efficiency is about 35% to 40% (International Energy Agency, 2007; U.S. Department of Energy, 2011). While high efficiency CHP plants can only be built in limited locations where residual heat can be delivered to final consumers, modern high-efficiency fireplaces can potentially be installed in any residence. Moreover, there are over 100 million households in the U.S. and an estimated 10 million family forest land owners (Butler, 2010). Millions of U.S. households living close to forests have easy access to wood energy feedstocks that could be utilized in high-efficiency modern wood stoves.

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A recent flurry of public policies at the U.S. federal and state levels has been adopted to promote wood energy consumption and production to address national security and climate change concerns (Aguilar and Saunders, 2010; Aguilar et al., 2011; DSIRE, 2010). However, existing U.S. major public policies such as the Public Utility Regulatory Policies Act (PURPA), energy production tax credit (PTC), federal business energy investment tax credit (ITC), loans, grants, and Renewable Portfolio Standards (RPS) instituted by individual states target electricity generation from renewable sources in power plants only, neglecting residential wood energy utilization. Although the Federal Residential Energy Efficiency Tax Credit program is applicable to residential biomass energy production, it is eligible to qualified purchasing and installation of a biomass heating system with up to a $500 tax credit as of 2011.

In spite of significant public interest in renewable energies and higher efficiency, U.S. household wood energy consumption patterns have garnered little research analysis in recent years. The latest journal article studying U.S. residential wood energy consumption included in the Energy Citation Database (U.S. Office of Science and Technological Information, 2011) is Warsco (1994). Warsco's study investigated the amount of conventional fuel displaced by wood using the 1984–1985 U.S. Residential Energy Consumption Survey (RECS) data (EIA, 2009b). Hardie and Hassan (1986) estimated residential energy consumption with the same RECS data used by Warsco (1994) but applied a different analytical method. Skog and Manthy (1989) studied U.S. fuelwood consumption using 1981 county-level cross sectional data and investigated the effects of price of non-wood energy and household income on household wood energy consumption. Skog (1993) projected wood energy use in the U.S. from 1986 to 2040 using a linear programming time series model. Warsco (1994), Skog (1993), and Hardie and Hassan (1986) concluded that wood was replacing other conventional energy sources in U.S. households and projected potential growth in its use as an energy feedstock. Historical data, however, show that energy from wood sources began to decline after 1985 and that wood stopped replacing other conventional energies (EIA, 2010). A lack of analyses of household wood energy consumption using the most up-to-date data from the RECS and the potential for the residential sector to use wood energy as a renewable energy motivated our study of factors affecting wood energy consumption by U.S. households.

The 2005 RECS data show that wood energy is mainly used by U.S. households for heating purposes. As shown in Table 1, a total of 548 RECS sampled households (13% of the total 4382 sampled households) used wood energy in 2005 (EIA, 2009b). In 2005 about 2% of residential wood energy was used by households that depend exclusively on wood for main and secondary heating, 43% of the residential wood energy was used for main heating purposes only, and 44% for secondary heating only. Out of the 548 households burning wood, 91% burned solid firewood from logs, 8% wood used scrap, and 6% used pellets (EIA, 2009b). Firewood remains the main feedstock of residential wood energy in the U.S.

Residents in rural areas constitute the major users of wood energy. U.S. rural households consumed more than twice as much as those in non-rural areas combined in 2005 (RECS 2005). Sampled households in U.S. rural areas used 12,270 GJ of wood energy while sampled households in other areas (i.e. cities, towns and suburban areas) used only 5296 GJ (EIA, 2009b). Previous studies based on data from the 1980s have shown similar patterns that reflect differences in wood energy consumption between rural and other residents (Hardie and Hassan, 1986; Skog and Watterson, 1984).

The households in the four U.S. regions (Northeast, Midwest, West, and South) identified by the U.S. Department of Energy (DOE) also behaved differently from each other according to the 2005 RECS. There were 9%, 13%, 12%, and 16% of sampled households using wood energy in U.S. Northeast Midwest, West, and South, respectively. The average amount of wood energy used by these households also differed. The means of wood energy consumed by households in the U.S. Northeast, Midwest, South, and West were 4.4, 5.4, 3.0, 4.0 GJ, respectively, in 2005. Regional differences in wood energy consumption were also discussed by Skog and Watterson (1984) and Hardie and Hassan (1986).

The objective of this study was to identify and parameterize factors affecting individual U.S. household wood energy consumption. Starting with the premise that households optimize their energy use by complementing wood and non-wood energy sources we describe our conceptual framework in the next section. Empirically, we used different models to capture regional and urban/rural setting differences in wood energy consumption. Eight left-censored Tobit regressions were estimated with data of individual households for urban and rural areas of each of the four U.S. Census regions (Northeast, Midwest, South and West). Estimates of marginal effects of explanatory model variables on regional, urban, rural and total U.S. residential wood energy consumption were calculated and are presented in the Results section. We discuss the implications of marginal effects and elasticities and conclude stressing policy implications and lines for future research.

2. Conceptual framework

It is noticeable that most U.S. households do not burn wood to produce energy; hence, there is a large number of ‘0’ values associated with wood energy consumption. An attempt to use ordinary least square estimates to model household wood energy consumption with a large proportion of zero observations would result in biased estimates (Greene, 1981). Therefore, Tobit models (after Tobin, 1958) were estimated to generate both zero and non-zero values of the dependent variable (i.e. wood energy consumption per household) to account for a non-trivial number of zero observations. This method has been widely used in applied econometric studies (e.g. Amemiya, 1984; Brehanu and Fufa, 2008; McPherson et al., 2001) and studies of household behavior (e.g. Bolkesjo and Baardsen, 2002, and Kuuluvainen and Tahvonen, 1999).

In our model the observed wood energy consumption (y) of a household takes ‘0’ or a positive value. The relationship between the censored y and independent variables can be expressed by a general Tobit model (Greene, 2002, Wooldridge 2002):

$$\begin{aligned} y &= \max(0, y^*) \\ y^* &= \beta X + \varepsilon, \end{aligned} \tag{1}$$

where y^* is the unobserved latent variable, $\boldsymbol{X}$ is a vector of explanatory variables, and $\boldsymbol{\beta}$ is a vector of corresponding model coefficients.

Table 1
Numbers of households (out of 4382 sampled households) using wood feedstock as primary or secondary heating sources and corresponding amount of energy consumed in 2005.

Uses	Number of households out of 4382 sampled households (%)	Average household wood energy consumption (GJ)	Total wood energy by sampled households (GJ)	Percent of wood energy by uses (%)
Main and secondary heating	5 (<1%)	86.5	433	2
Main but not secondary heating	103 (2%)	72.7	7486	43
Secondary but not main heating	333 (8%)	23.1	7718	44
Other uses (not heating)	107 (2%)	18.0	1931	11
All uses	548 (13%)	35.4	17,566	100

Source: EIA (2009b).

The ε is a random error following a normal distribution with mean zero and standard deviation σ. Under this model a household consumes wood energy only when the latent variable y^* takes a positive value, and the actual consumption $y = y^*$. Otherwise, the household does not use wood energy and $y = 0$.

This censored model has three expected values of y and y^*: (1) the expected value of latent variable $E[y^*]$, (2) the expected value of the observable dependent variable $E[y]$, and (3) the conditional expected value of $E[y|\ y > 0]$. The three derivatives of expectations of dependent variables with respect to $\boldsymbol{X}$ are the model's three corresponding marginal effects (Greene, 2002; McDonald and Moffitt, 1980; Sigelman and Zeng, 1999). The coefficients in vector $\boldsymbol{\beta}$ are the expected marginal effects of variables on the latent variable. The conditional marginal effects of variables are for households that currently burn wood. Because estimating the overall response of wood energy consumption by households in the U.S. was the purpose of this paper, the marginal effects on the observable dependent variable are our central focus. The marginal effect of the kth variable X_k on y can be expressed as in Eq. (2) (Greene, 2002).

$$\frac{\partial E[y]}{\partial X_k} = \beta_k \Phi\left(\frac{\beta' X}{\sigma}\right), \qquad (2)$$

where $\phi\left(\frac{\beta' X}{\sigma}\right)$ is the cumulative density function (*cdf*) of the standard normal distribution with argument $\frac{\beta' X}{\sigma}$, and β_k is the kth parameter in the parameter vector β. Because the *cdf* of a normal distribution is less than one, the marginal effect of explanatory variables expressed by $\beta_k \phi\left(\frac{\beta' X}{\sigma}\right)$ is less than its corresponding coefficient β_k. The standard deviation σ and coefficients in vector $\boldsymbol{\beta}$ are parameters to be estimated (Greene, 2002).

3. Empirical model

Households choose a combination of wood and non-wood energy to maximize their utility derived from heating. Residential wood energy consumption is determined by numerous factors associated to home heating including characteristics of household members (such as numbers of household members and age level of head of household), wood energy price, non-wood energy price, household income, house size, local weather, location (e.g. region, urban/rural area, and census division) and year when the home was built (Hardie and Hassan, 1986; Hardie and Scodari, 1982; Leth-Petersen, 2002; Mackenzie and Weaver, 1986; Scodari and Hardie, 1985; Skog and Watterson, 1984, and Warsco, 1994). Household wood energy demand is also affected by location (i.e. households in different U.S. regions and urban/rural areas consume wood energy at various levels). Variation in levels of wood energy consumption between U.S. regions and urban/rural households can stem from differences in the availability and price of wood energy feedstock as well as intrinsic household heating preferences. It is worth mentioning that values for wood energy prices are not available in the RECS 2005 and, thus, a structural model with both demand and supply equations was not possible to estimate. However, wood energy price and consumption are simultaneously determined by the same set of exogenous variables of demand and supply equations. Hence, a reduced form consumption model without own price can be estimated consistently (Greene, 2002; Jarrow and Protter, 2004; Varian, 1992).

Variables used in the Tobit models for U.S. household wood energy consumption are described in Table 2. Annual wood energy consumption (*WOOD*) of a household expressed in GJ corresponds to the dependent variable y in Eq. (1). To capture the differences of wood energy consumption by households, one model was estimated for each of the urban/rural areas in the four U.S. regions. A composite price of non-wood energy (*PNW*) weighted by amounts of five non-wood energy sources used by households was included as an

Table 2
Variable descriptions, measurement units, and justifications for being used in modeling U.S. household wood energy consumption [a].

Variable	Description	Justification
WOOD	Wood energy consumption per household in GJ.	Model dependent variable
PNW	Price of non-wood energy in dollars per GJ, total payment for non-wood energies divided by total GJ of non-wood energy consumed by a household. Non-wood energies include natural gas, electricity, fuel oil, liquefied propane, and kerosene [a].	Non-wood energy is a substitute for wood energy.
NHM	Number of household members.	Household size affects total heating demand.
AGHH	Age of head of household.	Age affects heating preference.
HINC	Household income in thousand dollars [a].	Income affects energy heating preferences.
THSQ	Total house area in square meters [a].	Building area affects heating.
AHDD	Annual sum of HDD in degree days, HDD is the degrees below 18.3 C° in a day [a].	Lower temperatures associated to higher heating demand.
YC	Year-of-construction, the year when a house was built.	New and old houses were built with different heating equipment and weatherization standards.
YC90	$YC90 = YC - 1990$ if $YC >= 1990$; $YC90 = 0$ if $YC < 1990$.	Capture changes in modeled relationships for houses built after 1990.
TOWN	One for town and zero for other locations.	Households in cities, towns, and suburbs differ in wood energy use. City is the base level in urban models
SUBURB	One for suburb and zero for other locations.	
RURAL	One for rural and zero for other locations.	Supply and demand are different in urban and rural areas. Used to split data between rural and urban models.
D_l	Dummy variables for subdivisions. $D_l = 1$ for household in division l, and 0 otherwise. In U.S. Northeast, $l = 1$ for New England and 2 for Middle Atlantic. In U.S. Midwest, $l = 3$ for East North Central, and 4 for West North Central. In U.S. South, $l = 5$ for South Atlantic, 6 for East South Central, and 7 for West South. In U.S. West $l = 8$ for Mountain, and 9 for Pacific.	Census divisions differ in wood consumption. One dummy variable in each region was excluded to avoid perfect collinearity. Coefficients of D_l are comparable within individual regions only.
REGION	1 = Northeast Census Region. 2 = Midwest Census Region. 3 = South Census Region. 4 = West Census Region.	Households in different regions behave differently. Used with *RURAL* variable to split data into eight models.
w	Number of households a sampled household represents.	Used as weight in estimating model coefficients, urban/rural, regional, and total U.S. marginal effects.

[a] : Original data for *WOOD*, *HINC*, *THSQ*, and *AHDD* were given in thousand Btu, U.S. dollars, square feet, and Fahrenheit degree days respectively. These units were converted into metric units in GJ, thousand U.S. dollar, square meter, and Celsius degree day for achieving convergent estimation. 1 Btu = 1055.05585262 J (EIA, 2010).

explanatory variable to capture substitution effects of competing non-wood energy alternatives (High and Skog, 1990 and Skog and Watterson, 1984). Non-wood energy sources for U.S. households include natural gas, electricity, fuel oil, liquid propane, and kerosene (EIA, 2010).

The number of household members (*NHM*) was included to estimate household size effect. *Ceteris paribus*, we expect that larger households consume more energy than smaller ones. Age of the head of household (*AGHH*) was included to capture possible differences in wood energy preferences across age groups. Total household income (*HINC*) was included as it has been reported to affect total energy demand as well as household wood energy consumption (Hardie and Hassan, 1986). The effect of household income has also been shown to change over income levels (Skog 1989). To explore this variation in income effect the square of household income ($HINC^2$) was included in the consumption model following Skog and Manthy (1989). Annual Heating Degree Day (*AHDD*) was used to estimate local weather effects on household wood energy consumption. *AHDD* is the yearly summation of daily heating degree days that was computed by subtracting 18.3 °C (65 °F) from the average of a day's high and low temperatures; negative values were set equal to zero (EIA, 2011). The bigger a house the more the energy that is necessary to heat it; thus, total house square meters (*THSQ*) was included in the model to capture such effect. The year-of-construction (*YC*) of a house was used to capture the effect of variation of heating equipment installed at different times that can consequently affect wood energy consumption. To estimate an observed change in the effect of *YC* between 1990 and 2005, another variable *YC90* was created. $YC90 = YC - 1990$ for $YC > 1990$, and $YC = 0$ otherwise. This variable allowed the model to capture changes in household wood energy consumption with respect to year-of-construction after 1990.

Whether a household is located in an urban or rural area affects wood energy consumption behavior as previously discussed. A binary variable *RURAL* identifying rural area was used to split the data. Urban areas were defined to include towns, suburbs, and cities. Binary variables *TOWN* and *SUBURB* were used for households located in a town or suburbs, respectively. *TOWN* and *SUBURB* were included in models for urban areas and measured the difference between wood energy consumption of a household in a town/suburb area and a household in a city.

Variable *REGION* listed in Table 2 was used along with *RURAL* to group data by U.S. regions and areas (urban or rural) for the eight Tobit models. Households in the U.S. were classified geographically into nine U.S. census divisions (U.S. EIA, 2010) identified with binary variables D_l, where $l = 1$ to 9. The relations among divisions and regions are shown in Table 2. Because models for each region were estimated separately, four of these binary division variables, one in each of the regions (D_2 in region 1, D_4 in region 2, D_7 in region 3, and D_9 in region 4), were excluded as base levels. Inclusion of division dummy variables helped improve estimations of individual regional equations by capturing divisional differences in household wood energy consumption. Nonetheless, an overall division effect cannot be determined because four models were estimated independently for the four distinctive U.S. regions. The weight *w* represents the number of households represented by an observation. It was also used in calculating descriptive statistics and marginal effects.

The empirical Tobit model used to estimate U.S. household wood energy consumption is presented in Eq. (3):

$$\begin{aligned} WOOD_{ij} &= max\left(0, WOOD_{ij}*\right); \\ WOOD_{ij}* &= \beta_{ij0} + \beta_{ij1}PNW_{ij} + \beta_{ij2}NHM_{ij} + \beta_{ij3}AGHH_{ij} + \beta_{ij4}HINC_{ij} \\ &\quad + \beta_{ij5}HINC_{ij}{}^2 + \beta_{ij6}THSQ_{ij} + \beta_{ij7}AHDD_{ij} + \beta_{ij8}TOWN_{ij} \\ &\quad + \beta_{ij9}SUBURB_{ij} + \beta_{ij10}RURAL_{ij} + \textstyle\sum_{l=1,3,5,6,8}\beta_{ij.l+10} * D_l + \eta_{ij}. \end{aligned} \tag{3}$$

In Equation 3, $i = 1, 2, 3,$ or 4 for the four U.S. census regions; $j =$ "urban" or "rural" for urban or rural areas; $l = 1, 3, 5, 6,$ or 8 for U.S. census divisions. $WOOD_{ij}$ and $WOOD_{ij}{}^*$ are the observed and potential amounts of wood energy consumed by a household in region *i* and area *j*. The two variables correspond to *y* and y^* in Eq. (1). The coefficients of explanatory variables are β_{ijm}, $m = 0, 1, \ldots, 10, 11, 13, 15, 16,$ or 18; η_{ij} is the error term. Following Eq. (2), marginal effects at means with respect to the *k*th variable (except $HINC_{ij}$ and $HINC_{ij}^2$) can be computed by Eq. (4):

$$\partial \mathrm{E}\left[\frac{WOOD_{ij}\left|\overline{X}_{ij}\right.}{\partial X_{ijk}}\right] = \beta_{ijk}\Phi\left(\frac{\beta_{ij}\overline{X}_{ij}}{\sigma}\right). \tag{4}$$

$\overline{X}_{ij}$ represents the weighted mean of vector X_{ij} for households; X_{ijk} is the *k*th explanatory variable for region *i* and area *j*. Based on Greene (2002), McDonald and Moffitt (1980), and Maddala (1983), the marginal effect of household income ($HINC_{ij}$) at means of variables for households in region *i* and area *j* is:

$$\partial \mathrm{E}\left[\frac{WOOD_{ij}\left|\overline{X}_{ij}\right.}{\partial HINC_{ij}}\right] = \left(\beta_{ij4} + 2\beta_{ij5}\overline{HINC}_{ij}\right)\Phi\left(\frac{\beta_{ij}\overline{X}_{ij}}{\sigma}\right). \tag{5}$$

$\overline{HINC}_{ij}$ is the weighted mean of $HINC_{ij}$. To capture the variation in the marginal effect of household income brackets reported by Skog and Manthy (1989), households for each model (i.e. region *i* and urban/rural area *j*) were classified into high-income and low-income groups. Those with income higher than the U.S. weighted household annual income median were labeled as high-income group, and the others as low-income group. The marginal effect of $HINC_{ij}$ for each group of households was computed at its corresponding mean value (i.e. marginal effects were estimated at the mean incomes of the high- and low-income groups). Wood energy consumption elasticities with respect to $HINC_{ij}$ were also computed for high-and low-income household groups at their respective income mean values.

Marginal effects and elasticities with respect to other variables for region *i* and urban/rural area *j* were estimated with all the observations in the corresponding region and area. Average marginal effects and elasticities of variables at regional and U.S. national levels were also computed. The software package SAS was used to estimate all models.

4. Data

Data for all the variables were either directly collected or derived from the database of 2005 RECS–the most recent survey information on household energy consumption by the DOE at the time of this study (EIA, 2009b). The survey unit of observation was an individual household. The value of weight (*w*) for each sampled household was computed by EIA based on the survey design, adjustments for non-response bias, and a final adjustment for the total weight of the survey to represent the total 111 million households of the U.S. in 2005 (EIA, 2009b, 2009c). Table 3 presents descriptive statistics for all variables.

Two sampled households in the 2005 RECS data have unrealistically large electricity prices (i.e. values with more than 10-standard deviations away from their regional means). These two observations were excluded from the models as were deemed to be outliers. Outliers could represent error records or special households and represented only 0.05% of the total number of observations. A total of 4382 observations were used in the estimation.

Data for household wood energy consumption *WOOD* were derived from the total woody material reported for households in the 2005 RECS. Woody material is comprised by the amount of logs, split logs, scrap, and other wood a household burned. Note that

Table 3
Weighted means of variables used in the household wood energy consumption models by U.S. regions and areas[a].

Variables (units)	U.S. Northeast		U.S. Midwest		U.S. South		U.S. West	
Areas	Urban[b]	Rural	Urban	Rural	Urban	Rural	Urban	Rural
Models	1	2	3	4	5	6	7	8
WOOD (GJ)	1.02	23.03	1.66	20.26	1.10	8.69	2.32	13.95
PNW ($/GJ)	21.33	23.50	17.01	20.66	24.43	26.16	21.85	22.62
NHM (people)	2.61	2.32	2.48	2.41	2.49	2.60	2.78	2.60
AGHH (year)	51.05	52.82	49.47	52.22	48.87	52.33	47.85	54.15
HINC (thousand US$)	48.36	51.57	46.32	54.14	48.09	40.36	54.75	55.68
THSQ (m^2)	148.60	186.78	164.95	234.64	143.33	146.22	120.84	162.46
AHDD (degree days)	3144	3560	3287	3409	1374	1716	1561	2548
YC (year)	1960	1967	1967	1973	1977	1979	1972	1976
YC90 (year)	0.82	1.21	1.59	2.09	2.29	2.63	1.38	2.39
TOWN (N/A)	0.35	–	0.25	–	0.16	–	0.15	–
SUBURB (N/A)	0.25	–	0.28	–	0.25	–	0.24	–
n[c]	810	156	769	190	1029	383	898	145
Total weight[d] (thousands)	17,344	3222	20,417	5187	30,292	10,391	20,646	3546

[a] The means of *D1* to *D8* are not included in this table. Two outliers were excluded from the sample.
[b] Urban in this table means all areas that are not rural.
[c] *n* is the number of observations.
[d] Total weights are the sum of the weights (*w*) of sampled households in the corresponding areas.

pellets were not included in household wood energy consumption as the amount of pellet consumption was not asked in the 2005 RECS survey. The small number of households using pellets (6% of sampled households burning wood) indicates that the missing amount of wood energy consumption from pellets was trivial. Data for *WOOD* and *HINC* are midpoint values of intervals (EIA, 2009b). It is worth mentioning that the original RECS wood consumption amount was given in cords, a U.S. measure for firewood that is equivalent to about 3.6 m^3 of stacked firewood. The heat value used in this study for a cord was 21.1 GJ (20 million Btu). The means of variables presented in Table 3 were weighted by *w*. Total weights in this table represent numbers of households located in urban and rural areas of each U.S. region. These weights represent 89 million urban and 22 million rural U.S. households. The weighted mean for wood energy consumption (*WOOD*) of a rural household in the U.S. Northeast was 23.03 GJ, the largest of the eight models. For urban household in the same region the weighted mean of *WOOD* was only 1.02 GJ, the least for the eight models. The means of *WOOD* in rural areas were greater than those in urban areas in all the four regions. The non-wood energy price for *PNW* in dollar per GJ ($/GJ) for each household was calculated by dividing total dollar payment for non-wood energy consumed by number of GJ of the non-wood energy. The means for non-wood energy *PNW*, number of household members *NHM*, and age of the head of households *AGHH* do not vary much across urban\rural areas and regions. Consistently, average floor area of houses *THSQ* in rural areas across the four regions are larger than those in urban areas. Large means for *ADHH* for U.S. Northeast and Midwest indicate colder winter seasons.

The values of *TOWN*, *SUBURB*, and *RURAL* were self-reported by households in the 2005 RECS survey. The means of dummy variables for *TOWN* and *SUBURB* represent the proportions of households located in towns and suburbs. Based on the total weights in Table 3, there were a larger proportion of rural households in the U.S. South compared to other regions. The U.S. West was the most urbanized with the smallest proportion of rural households.

Table 4
Estimated coefficients of Tobit models for U.S. household wood energy consumption by regions and areas [a].

Regions	U.S. Northeast[b]		U.S. Midwest[b]		U.S. South[b]		U.S. West[b]	
Areas	Urban	Rural	Urban	Rural	Urban	Rural	Urban	Rural
Models	1	2	3	4	5	6	7	8
Constant	1316.9	3016.2	18.8	187.2	−1145.5	738.6	112.2	−182.2
PNW	0.949	5.319	1.310	9.269	−0.394	2.566	−0.094	3.247
NHM	0.667	19.298	3.943	12.824	0.015	2.243	2.057	4.441
AGHH	−0.001	−0.477	0.444	3.378	0.163	0.097	0.290	0.945
HINC	−0.939	2.225	0.578	1.566	0.642	0.231	1.065	0.543
$HINC^2$	0.010	−0.020	−0.003	−0.011	−0.004	−0.002	−0.006	−0.005
THSQ	0.041	0.251	0.062	0.111	0.026	0.196	0.054	0.053
AHDD	0.015	0.074	0.005	0.001	0.004	0.022	0.003	0.017
YC	−0.759	−1.823	−0.094	−0.357	0.547	−0.467	−0.113	−0.021
YC90	−3.242	−2.444	−1.478	1.409	−2.184	−1.506	−3.842	−2.037
TOWN	13.689		5.488		6.983		9.860	
SUBURB	28.934		−0.557		−3.002		8.121	
D1	8.583	−73.461						
D3			−7.830	−7.426				
D5					−5.788	−16.593		
D6					−0.519	−11.365		
D8							−1.766	12.739
σ [b]	48.935	131.857	50.314	87.788	29.034	64.195	39.741	50.799
LR tests *p*-value[c]	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

[a] The *p*-values for the estimated coefficients are all less than 0.01.
[b] Values corresponding to σ are standard deviations of the residuals of the Tobit models.
[c] Likelihood ratio tests are for the significance of the estimations with the hypothesis that all coefficients except intercept are simultaneously zero for a model.

Table 5
Marginal effects of selected explanatory variables on individual household wood energy consumption in urban and rural areas of the four U.S. regions computed at weighted means of explanatory variables[a].

Variables (units)	U.S. Northeast		U.S. Midwest		U.S. South		U.S. West	
Models	1	2	3	4	5	6	7	8
Areas	Urban	Rural	Urban	Rural	Urban	Rural	Urban	Rural
PNW	0.01	1.50	0.10	3.08	−0.03	0.55	−0.01	1.16
NHM	0.01	5.43	0.31	4.26	<0.01	0.48	0.27	1.59
AGHH	<0.01	−0.13	0.03	1.12	0.01	0.02	0.04	0.34
HINC[b] (*low-income*)	−0.01	0.26	0.02	0.28	0.02	0.03	0.05	0.09
HINC[c] (*high-income*)	0.02	−0.29	0.02	−0.08	0.01	−0.02	0.00	−0.11
THSQ	<0.01	0.07	<0.01	0.04	<0.01	0.04	0.01	0.02
AHDD	<0.001	0.023	<0.001	<0.001	<0.001	0.003	0.001	0.007
YC	−0.01	−0.51	−0.01	−0.12	0.04	−0.10	−0.01	−0.01
YC90	−0.05	−0.69	−0.11	0.47	−0.17	−0.25	−0.51	−0.73

[a] All marginal effects are based on estimated coefficients in Table 3; Weights are values of *w*.
[b] Marginal effects of income estimated at means of households whose income ≤ U.S. median income.
[c] Marginal effects of income at means of households whose income > U.S. median income.

5. Results

All eight left-censored Tobit models converged and all *p*-values of the likelihood ratio tests for the significance of these models were less than 0.001. The *p*-values of all estimated coefficients were less than 0.01 (Table 4) suggesting that all explanatory variables had a significant effect on household wood energy consumption. The impact on wood energy consumption of a change in price of non-wood energy, number of household members, age of head of household, total housing area, AHDD and year of construction was derived from corresponding marginal effects (Eq. 4) and presented in Table 5. Below we describe divisional differences and variation among households in urban areas before discussing the effects of these variables.

Urban areas distinguished between households in a city, town and suburban area. The positive coefficients of *TOWN* suggest that a household in a town is expected to use more wood energy than its base level (i.e. city). The signs of the estimated coefficients of *SUBURB* were mixed across models. The signs of coefficients of this variable suggest that an average household in suburban areas in the Northeast and West used more wood energy than one in a city in these regions, but in the Midwest and South regions the opposite was found. *Ceteris paribus*, negative coefficients for division dummy variables suggest that a rural household in New England (*D1*) used less wood energy than one in the Middle Atlantic division (*D2*); households in rural and urban areas of the East North Central division (*D3*) used less wood energy than those in their corresponding areas of the West North Central division (*D4*). Likewise, households in rural and urban areas of South Atlantic division (*D5*), at the average, consumed less wood energy than those in their corresponding areas of the West South division (*D7*); households in East South Central division (*D6*), urban and rural, on average consumed less wood than those in their corresponding areas of the West South division (*D7*); urban households in the Mountain division (*D8*) on average consumed less wood energy than those in the Pacific division (*D9*). Holding other variables constant, households in urban areas of New England (*D1*) and rural areas of Mountain division (*D8*) consumed more wood energy than those in their corresponding area of base level Middle Atlantic (*D2*) and Pacific division (*D9*), respectively.

Expected marginal effects on household wood energy consumption included in Table 5 were calculated at the means of corresponding explanatory variables. Two rows of marginal effects of household income (*HINC*) were computed following Eq. (5) at means of variables for high- and low-income household groups. Marginal effects of non-wood energy price *PNW* were positive in six of the eight models, with the greatest effect for Model 4 (Midwest rural households). The marginal effect of *PNW* in urban areas of the South and West regions are negative. Our explanation for the negative sign of the marginal effect of alternative energy on wood energy consumption in urban areas is that high alternative energy prices increase the demand for wood fuel in rural areas but in turn can reduce the wood fuel supply for urban households and finally its consumption. The net effect of the increment and reduction is negative for the two models. The estimated marginal effects of *PNW* for the rural models are larger than those for urban models.

The signs of the estimated marginal effect of *NHM* are positive for all the eight estimated models, suggesting that an increase in the number of household members resulted in more wood energy consumed *ceteris paribus*. The estimated marginal effects of *NHM* for the rural areas were also larger than those for urban areas in all the four U.S. regions. Six out of eight of the estimated marginal effects for *AGHH* are positive, suggesting that older heads of households tend to use more wood energy in three of four U.S. regions. The effect of household income varied with income level as shown by Skog and Manthy (1989). Seven out of eight of the marginal effects of *HINC* for low-income households were positive. The marginal effects of *HINC* were positive for high-income households in urban areas but negative in rural areas. The estimated marginal effects of *THSQ* and *AHDD* are positive for all the eight models, showing that larger houses or houses in colder areas consume more wood energy.

The signs for estimated marginal effect of *YC* and *YC90* are predominantly negative (Table 5). The sum of the estimated coefficients

Table 6
Weighted average marginal effects of selected variables on household wood energy consumption by households in urban and rural areas and corresponding elasticities[a].

Areas	Urban		Rural		U.S.	
Variables	Marginal effects	Elasticities	Marginal effects	Elasticities	Marginal effects	Elasticities
PNW	0.01	0.18	1.37	2.30	0.29	1.55
HINC (*low-income*)	0.02	0.42	0.13	0.20	0.04	0.24
HINC (*high-income*)	0.01	0.42	−0.09	−0.48	−0.01	−0.15
THSQ	<0.01	0.34	0.04	0.51	0.01	0.41

[a] Values are computed based on Table 5.

of these two variables are negative for seven out of eight of the models with positive sums for the rural Midwest as an exception, suggesting that at the average newer houses in the U.S. tend to use less wood energy except those in the rural Midwest.

The effects of factors such as non-wood energy price, income and house areas interest us the most due to associated policy implications. Marginal effects in Table 6 capture differences in responses of average households in U.S. urban and rural areas. While the marginal effect on household wood energy consumption of a one dollar change for one GJ of non-wood energy (*PNW*) was estimated to be 0.01 in U.S. urban areas, the effect in U.S. rural area was estimated to be 137 times greater. The marginal effect of income (*HINC*) was positive for low-income households in both urban and rural areas and high-income households in urban areas, but such marginal effect is negative for high-income rural households, suggesting that, *ceteris paribus*, an average high-income U.S. household in rural areas tend to use less wood energy when their income grows. The marginal effect of a change of one square meter of floor area (*THSQ*) was smaller for urban households compared to rural ones.

Elasticities presented in Table 6 represent percent differences in wood energy consumption as a result of a 1 percent change in the mean value of an explanatory variable. The largest elasticities corresponded to the effect of a change in price of non-wood energy. Elasticities with respect to non-wood energy price *PNW* and house square meters *THSQ* for households in rural areas were larger than those in urban areas. Note that the elasticity with respect to non-wood energy price was 2.30 for rural households but only 0.18 for urban households. The elasticities with respect to house size were positive and less or equal to 0.51 for both U.S. urban and rural households. The elasticity with respect to income was 0.42 for both low- and high-income urban households, larger than low-income rural households (0.20). The elasticity with respect to income among high-income rural households however was −0.48 suggesting wood energy was an inferior good for this group. National U.S. elasticities with respect to *PNW*, *HINC* for low-income households and *THSQ* were all positive. The only negative elasticity was associated with income effects among high-income groups, suggesting that nationally a one percent increase in income among high-income households would result in a 0.15 percent reduction in wood energy consumption, *ceteris paribus*.

To analyze differences of marginal effects of variables for households in the four regions, weighted averages of marginal effects of selected variables on household wood energy consumption were calculated with estimates from Table 5 and corresponding weights. These marginal effects and elasticities are shown in Table 7.

The estimated marginal effects of *PNW*, *HINC* for low-income households, and *THSQ* were positive in all four regions. The estimated marginal effects of *HINC* for high-income households were negative in three of the four U.S. regions. The marginal effect of *PNW* for household in the U.S. Midwest (0.71) was larger than those for the other regions; the elasticity with respect to *PNW* in the U.S. Midwest (2.31) was also larger than those in other regions. Elasticities with respect to *PNW* were consistently greater than the other two economic variables in all four regions.

6. Discussion

The 2005 RECS weighted average U.S. household consumption of wood energy was 1.50 GJ in urban areas and 14.28 GJ in rural areas. We estimated that 80% U.S. households in urban areas consumed about 30% of U.S. residential wood energy while the other 20% U.S. households in rural areas used 70% of U.S. residential wood energy. The fact that the lion's share consumption of wood energy was done by households in rural areas has direct implications. The number of occupied rural and suburban households in the U.S. has declined from 28,680 thousand in 1997 to 27,969 thousands by 2007, at an average of 201 thousand households per year (U.S. Census Bureau, 2011). A shrinking rural population in the U.S. is likely to result in a reduction in residential wood energy consumption unless other factors that promote wood energy consumption such as non-wood energy prices increase to a level that offset this historic trend.

National residential wood energy consumption could be estimated with a single U.S. model, but such estimation would not provide detail information on statistically significant differences between regions, urban and rural household wood energy uses. Differences caused by the availability in energy resources, historic traditions, infrastructure, non-wood energy markets, among others in different locations can be captured through multiple models. The variation observed in our results stress the need of separate models for U.S. regions and urban/rural areas when studying U.S. household energy consumption.

Findings of Tobit models consistently suggest that U.S. households that paid a higher price for non-wood energy had a tendency to consume more wood energy. At a national level, U.S. household elasticity of 1.55 of wood energy consumption with respect to non-wood energy price suggests a good level substitutability of non-wood sources with wood energy. The effect of non-wood energy price on wood energy consumption is even more dramatic among rural households with an elasticity of 2.30. As prices for non-wood energy increase as a result of market or policy-induced effects it could be expected that, at the average, U.S. households would consume greater amounts of wood energy, and those in rural areas even more. Public intervention through market-based policies has been used to encourage renewable energy use. For instance, Ericsson et al. (2004) have suggested that taxes on fossil fuels are among the most efficient policy instruments in promoting use of woody biomass energy of European countries as they improve the cost competitiveness of wood energy. Results of our study suggest that a similar approach that increases the relative price of non-wood energy would encourage households to substitute it with wood energy.

Alternatively, lowering the cost of wood fuel for household consumption can also reduce wood energy price relative to non-wood energy alternatives and trigger greater wood energy consumption (Hardie and Hassan, 1986; Skog, 1993; Skog and Watterson, 1984). Aguilar and Saunders (2011), based on a survey of forest sector stakeholders, report that tax incentives (e.g. tax exemptions or credits) were perceived to be the preferred policy tool in promoting price competitiveness of renewable energy feedstocks followed by the

Table 7
Weighted marginal effects of selected variables on household wood energy consumption and corresponding elasticities by U.S. regions.

Regions	U.S. Northeast		U.S. Midwest		U.S. South		U.S. West	
Variables	Marginal effects	Elasticities	Marginal effects	Elasticities	Marginal effects	Elasticities	Marginal effects	Elasticities
PNW	0.25	1.20	0.71	2.31	0.12	0.96	0.16	0.87
HINC (*low-income*)	0.03	0.16	0.07	0.31	0.02	0.16	0.05	0.33
HINC (*high-income*)	−0.03	−0.52	<0.01	−0.02	0.01	0.12	−0.02	−0.45
THSQ	0.01	0.40	0.01	0.37	0.01	0.58	0.01	0.28

adoption of education and consultation programs, and rules and regulations. Advances in technology that lower the cost of local wood energy generation relative to non-wood energy price can also have a positive effect on household wood energy consumption. Highly-efficient residential heating systems are an example of how advances in technology can improve price competitiveness of wood energy. Preferential tax treatment for households installing-efficient wood-based systems could be an effective policy tool given the reported level of substitutability of non-wood for wood energy. The large marginal effect of non-wood energy price for rural households implies that policies enhancing the competitiveness of wood energy will have the greatest effect on residential wood energy consumption in U.S. rural areas. Public funding allocated to promote wood energy household consumption will be more effectively used if it targets rural areas.

The negative effects on residential wood energy consumption associated with the time houses were built reflect differences in wood energy consumption among newer and older houses. This effect suggest a downward trend in wood energy consumption over time as newly built houses use less wood energy. New building and urbanization effects partially may help explaining the observed decline in household wood energy consumption over the last 50 years (Aguilar et al., 2011). However, it is important to remember that the models presented in this paper were based on cross-section data from a single year (2005), hence, it is ill-suited to capture trends over time (e.g. technological progress) as inferences made about future changes based on cross-sectional data must assume that all other model conditions remain constant over time. A time-series model is a better option to forecast future conditions as other variables change over time. In spite of its limitations, our Tobit modeling approach was well suited to explore regional and urban/rural areas differences.

Our model could not capture wood energy consumption from pellets due to the fact that this information was not gathered as part of the 2005 RECS. Although reported residential use of wood pellets is minor, this shortcoming may have resulted in potentially underestimated total household wood energy consumption. Wood pellets have the potential to emerge as a major form of energy feedstock for some households in the U.S. residential sector. Omitting the wood energy price because of lack of data is another limitation of this model. This variable should be re-inserted in upcoming EIA household surveys for subsequent analysis.

Residential use of wood energy may have not attracted much attention in the U.S. in recent years as denoted by a lack of public policy or research addressing this sector. However, wood energy, particularly in rural areas, provides an important alternative to reduce household dependency on fossil fuels for heating. Wood energy utilization also allows for the production of energy locally, making local jobs and increasing energy security in the long-run. Moreover, a large number of U.S. families own forestland (Butler, 2010) that can be used as a source of wood energy feedstock. Harvesting of woody materials for energy, if done properly, can improve forest health conditions by providing opportunities for commercial thinning to remove low-quality trees, reduce fuel build-up and even improve conditions for wildlife habitat, among other benefits (Aguilar and Garrett, 2009). While the capacity of wood energy to reduce net greenhouse gas emissions is still under question, the combined benefits of wood energy use provide an argument to support and encourage its use in the U.S. rural sector.

7. Conclusions

This research investigated the factors that account for variation in the U.S. household heating wood consumption by estimating left-censored Tobit models for urban and rural areas of each of the four U.S. census regions as defined by the U.S. Department of Energy. Urban/ rural location is a key determinant of household wood energy use as rural households consumed 70% of U.S. residential wood energy, mainly for heating homes, in 2005. As expected, households in rural areas are more likely to burn wood for energy than households in cities, towns, and suburbs. Urbanization is associated with lower levels of wood energy use. Our results concur with past reports suggesting varying price and income effects on wood energy consumption by urban and rural households.

Given some key model assumptions non-wood energy price was estimated to have the largest marginal effect on household wood energy consumption, and in particular, among rural households. Its effect on total U.S. residential wood energy use was greater than household income. The estimated marginal effect of income varied with income level. At mean values of explanatory variables for low-income U.S. rural households the marginal effect of income was positive. However, it was negative for high-income U.S. rural households. As expected, holding other variables constant, households with more members tend to burn more wood. Older heads of households are more likely to use wood energy than younger ones, except in the Northeast. Residents of newer houses tended to consume less wood for energy than those living in older houses, and residents of new homes built after 1990 used substantially less wood energy than those in older homes. If residents of newer houses tend to have higher incomes then higher incomes may also be associated with lower wood use.

Because of lack of time dimension in the survey data, the estimated models have not captured the effects of factors changing over time — for example shift to more efficient wood stoves over time. A time series study of household wood energy consumption will serve to complement the findings of this paper. We were not able to estimate the effect of change in wood energy price on wood energy consumption for lack of wood fuel price paid by households. This is another limitation of this study. Results of past studies citied in this paper, however, showed that household wood energy consumption is also sensitive to its own price.

Public policies and market forces that reduce wood energy cost or increase costs of alternative fuels for households may promote the use of residential wood energy, especially in rural areas. U.S. household wood energy consumption would increase 1.55% for each percent increment in the price of non-wood energy. Based on estimated elasticities (i.e. additional wood energy consumption as a result of price changes), taxation of fossil fuels and tax credits on greater wood energy utilization may be effective policy tools to induce greater household wood energy consumption. The U.S. Midwest was estimated to have the greatest level of substitutability of wood with non-wood energy with elasticity 2.31. The fact that the U.S. Midwest region was the most responsive to changes in non-wood prices suggests that any public policy efforts aimed at promoting household wood energy consumption via price improvements will be most effective if targeting this region rather than the entire nation.

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