Energy Economics 34 (2012) 2116–2124

Contents lists available at SciVerse ScienceDirect

Energy Economics

journal homepage: www.elsevier.com/locate/eneco

Analysis of U.S. residential wood energy consumption: 1967–2009

Nianfu Song [a,*], Francisco X. Aguilar [b], Stephen R. Shifley [c], Michael E. Goerndt [b]

[a] Department of Forestry, University of Missouri, 203ANBR University of Missouri, Columbia, MO 65211, USA
[b] Department of Forestry, University of Missouri, Columbia, MO 65211, USA
[c] USDA Forest Service, Northern Forest Research Station, Columbia, MO 65211, USA

ARTICLE INFO

Article history:
Received 31 March 2011
Received in revised form 21 September 2011
Accepted 2 March 2012
Available online 13 March 2012

JEL classification:
C22
N72
Q23
Q41
Q42
R15

Keywords:
Woody biomass
Energy consumption
Cointegration

ABSTRACT

The residential sector consumes about 23% of the energy derived from wood (wood energy) in the U.S. An estimated error correction model with data from 1967 to 2009 suggests that residential wood energy consumption has declined by an average 3% per year in response to technological progress, urbanization, accessibility of non-wood energy, and other factors associated with a time trend such as increasing income per capita and number of houses. But the rising price of non-wood energy has had a positive effect on the consumption and offset the downward trend effect in the last decade. Residential wood energy consumption has also been sensitive to changes in wage rate in both long-run and short-run, but the total estimated wage rate effect since 1967 is negligible. Wood energy is expected to continue to account for a small share of residential energy consumption unless public policies improve wood energy cost competitiveness relative to non-wood energy.

1. Introduction

The utilization of woody feedstock as a renewable source of energy has garnered considerable attention because of its potential to ameliorate present societal dependence on fossil fuels. Woody biomass energy can be renewed indefinitely when forests are managed sustainably (Schlamadinger et al., 1995, Schwaiger and Schlamadinger, 1998). Regeneration of forests harvested to produce wood-based energy can reabsorb carbon from the atmosphere and potentially reduce the total amount of greenhouse gas emissions associated with energy generation over an extended period of time (Cannell, 2003). Direct combustion of wood and wood-derived liquid fuels is poised to become an important component of a comprehensive national energy portfolio intended to enhance energy security, economic development, and environmental protection (Aguilar and Garrett, 2009, U.S. Environmental Protection Agency, 2011a, 2011b).

Reducing the dependence of the U.S. on non-renewable fossil fuels is central to a global movement to increase renewable energy usage. The U.S. remains the world's largest consumer of energy; its annual energy consumption was 21% of the global total in 2009, more than the total energy used in Europe the same year. Currently, about 8% of the energy used in the U.S. comes from renewable sources (U.S. Energy Information Administration, 2010a). Although wood is no longer a major energy source in the U.S., it contributes the second largest proportion of renewable energy in the country. Total U.S. wood energy consumption in 2009 was 1995 PJ (1891 trillion Btu) or about 24% of the renewable energy used in the U.S.

About 23% of U.S. wood energy was consumed in the residential sector, 64% in the industrial sector, 9% in the electric utility sector, and 4% in the commercial sector (U.S. Energy Information Administration, 2010a, 2010b). Wood in the U.S. residential energy sector has been used mainly for heating purposes and has historically competed with other heating energies such as natural gas, electricity, and petroleum products (Hardie and Hassan, 1986, Howard and Westby, 2009, Skog and Manthy, 1989, Skog and Watterson, 1984). Wood energy in the residential sector has been derived mainly from firewood, chips, and pellets (Skog, 1993, U.S. Energy Information Administration, 2010c).

Wood energy used for residential heating can be an efficient use of a renewable feedstock since heat is directly released to homes when wood is burned. Current thermal efficiency of common stoves and fireplace inserts is 70–80%, comparable to a combined heat and power plant. In contrast, the efficiency of a typical U.S. power plant co-firing with coal and wood for electricity generation averages about 35–40% (International Energy Agency, 2007). Only one-third of the U.S. wood energy consumed by the electric utility sector is used by high efficiency combined heat and power plants (U.S. Department of Energy, 2011).

* Corresponding author.
E-mail addresses: songn@missouri.edu (N. Song), aguilarf@missouri.edu (F.X. Aguilar), sshifley@fs.fed.us (S.R. Shifley), goerndtm@missouri.edu (M.E. Goerndt).

0140-9883/$ – see front matter © 2012 Elsevier B.V. All rights reserved.
doi:10.1016/j.eneco.2012.03.004

The majority (96% by capacity) of biomass power plants that came on-line from 2005 to 2007 have a thermal efficiency of about 38% (U.S. Department of Energy, 2011).

The quantity of woody biomass energy potentially available has been estimated to be 6680 PJ (334 million dry tons) annually (Perlack et al., 2005). Current wood energy consumption in the U.S. is only about one-third of the energy potentially available from woody biomass. Moreover, about one-third of U.S. forests are owned by 10 million family forest owners (Butler, 2010), with many of those forests in close proximity to owners' homes. Thus, a large proportion of privately-owned U.S. forest biomass is located near potential residential wood energy users. Perlack et al. (2005) estimated that wood energy could theoretically meet up to 6% of the U.S. national energy demand. Achieving that level of wood energy utilization will certainly require the participation of residential wood energy users, many of whom, like the woody biomass resource itself, are widely dispersed across the landscape.

Biomass energy policies have been designed primarily to support biomass for electricity generation (or biomass power) (Aguilar et al., 2011). For example, the Public Utility Regulatory Policies Act was enacted in 1978. The U.S Federal Renewable Energy Production Tax Credit became applicable to biomass power in 1992. The Federal Business Energy Investment Tax Credit was extended to biomass electricity in 2009. The Federal Renewable Grants program was created in 2009. The Federal Green Power Purchasing Goal requires renewable energy to comprise a certain proportion of electricity used by the federal government since 2005. Several government bond programs have also been established to promote biomass power (Aguilar et al., 2011).

Only one federal policy, the Residential Energy Efficiency Tax Credit, has specifically targeted residential wood fuel use (DSIRE, 2011). Residents investing in high-efficiency biomass stoves that qualified for this program were eligible for a federal tax credit with a $1500 limit for purchases and installations in 2009 and 2010, but in 2011 the maximum tax credit was reduced to $500 (DSIRE, 2011). At the state level, several additional approaches have been adopted to promote greater residential wood energy use. For example, Alabama's Wood-Burning Heating System Deduction allows individual taxpayers a deduction for the purchase and installation of a wood-burning heating system (Alabama Department of Revenue, 2005). The deduction is equal to the total cost of purchase and installation for the conversion of a primary home heating system from gas or electricity to wood. Arizona's Qualifying Wood Stove Deduction allows Arizona taxpayers to deduct the cost of converting an existing wood fireplace to a qualified wood stove (Arizona Department of Commerce, 1994). The cost to purchase and install all necessary equipment is tax deductible in Arizona, up to a maximum of $500. Maryland's Wood Heating Fuel Exemption frees all wood or wood-derived fuel used for residential heating purposes from state sales taxes (State of Maryland, 2005). Aguilar and Saunders (2009) provide additional details about state-level policies promoting wood energy consumption.

The objective of this study was to investigate historical changes in U.S. residential wood energy consumption, identify factors that are significantly associated with wood energy consumption over time, use those factors to model wood energy consumption, and examine associated policy implications. First, historical data were used to graphically and statistically analyze trends in U.S. residential wood energy consumption and to identify variables associated with household wood energy consumption. Long- and short-run coefficients of an error correction model (ECM) were estimated after the identification of non-stationarity in these variables. Historical effects of changes of each explanatory variable on residential wood energy consumption are presented and their implications discussed. We analyzed the 1967–2009 period to explore factors affecting residential wood energy consumption over a four-decade timeframe, but we also studied changes over a shorter timescale (2000–2009) to better capture more recent variability.

This study is based on a time series model that facilitates analysis of residential wood energy consumption changes over time. Due to data limitations, the time series model cannot capture the regional (spatial) differences in residential wood energy consumption that have been reported in past studies (e.g., Hardie and Hassan, 1986, Skog and Manthy, 1989, Song et al. 2012). Consequently, geographical differences in household wood energy consumption are investigated in a separate study based on data from the U.S. Residential Energy Consumption Survey (RECS).

2. Historical trends and dynamics

The contribution of wood energy to U.S. residential energy consumption has experienced significant changes over time. In 1945, U.S. wood energy accounted for 23% of total residential energy consumption. It declined to 5% in 1967, and contracted further to 4% of the total residential energy consumption by 1973 (U.S. Energy Information Administration, 2010a). After the 1973 oil crisis, U.S. wood energy consumption by households enjoyed a decade of growth. The share of wood energy in the residential sector reached 10% in 1982, its highest level since 1959. Another decline in residential wood energy began in 1986 and by 1997 the residential wood energy share decreased again to about 4% and remained there through 2009 (Fig. 1).

The decline in U.S. residential wood energy use has been associated with urbanization, inefficiency of traditional fireplaces as compared to other heating systems, and competition from other sources of energy (Hardie and Hassan, 1986, Skog and Manthy, 1989, Skog and Watterson, 1984). Urbanization has made wood energy less accessible. Only 60% of the U.S. population lived in cities in 1950, but the percentage of urban residents increased to 79% by 2000 (U.S. Census Bureau, 2010b, 2010c). In the 20th century, oil, natural gas, and electricity became more available, and increasing levels of household income and decreasing fossil fuel prices have made the latter more affordable (U.S. Energy Information Administration, 2010a). In recent decades, natural gas, electricity, and petroleum products have replaced wood and coal and become the main sources of heating energy for U.S. households (U.S. Energy Information Administration, 2000, Warsco, 1994). When modern heating systems using non-wood energy provided additional convenience (i.e. no need to gather and process firewood) and easy-to-control temperatures, traditional low efficiency fireplaces became less attractive and were gradually phased out as heating equipment in most U.S. homes (U.S. Energy Information Administration, 2010c).

Coal represented about 27% of the total residential energy consumption in 1949 (U.S. Energy Information Administration, 2010a).

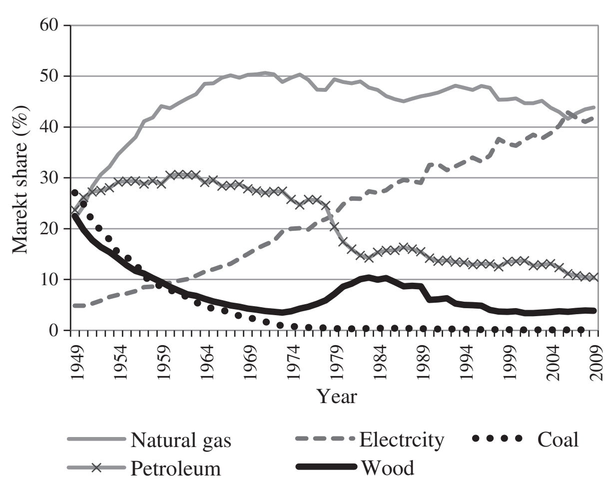

Fig. 1. Market share of U.S. residential energy consumption by energy sources. Source: U.S. Energy Information Administration (2010a).

Since then coal consumption by households has experienced a substantial decline. Unlike the market share of wood, the share of coal in the residential sector experienced an uninterrupted decline, and by 2009 its share contracted to less than 1% of residential energy consumption. The share of natural gas peaked at 51% of total residential energy consumption in 1971, but it gradually declined to 44% in 2009. Residential energy from petroleum products reached its maximum market share (31%) in 1961 but that share declined to 10% by 2009. Energy from petroleum products consists of liquefied petroleum gas, heating oil, and kerosene. The share of electricity in the residential sector increased in most of years since 1949 and reached 42% in 2009 (Fig. 1).

According to the 2005 RECS (U.S. Energy Information Administration, 2010c), about 2.5% of U.S. households used wood as the primary heating energy in 2005, but wood had been the most prominent household secondary heating fuel until 1997 when it was surpassed by electricity (U.S. Energy Information Administration, 2000). The percent of households using electricity as secondary heating fuel increased from 13% in 1978 to 15% in 1997 while the percent of U.S. households using wood as secondary heating fuel decreased from 21% to 13% over the same period (U.S. Energy Information Administration, 1999, 2000). From 1997 to 2005, the percent of households using wood as their secondary energy source further declined by 5% while electricity dropped by only 3%.

3. Econometric model

An econometric model was developed to analyze U.S. residential wood energy consumption over the 1967–2009 period. U.S. residential wood energy consumption is determined by demand from homes and supply from producers, some of whom are the residents within these homes. It is reasonable to assume that prices of non-wood energy such as natural gas, electricity, and fuel oil affect the residential wood energy demand because they are substitutes for wood fuel. Exploratory correlation analysis showed that these non-wood energy prices are highly linearly correlated with one another. Consequently, simultaneous inclusion of all of these linearly correlated variables in one model may not yield accurate estimates because of inflated variance (Greene, 2002). To eliminate the collinearity problem, a composite non-wood energy price was used in this study.

Residential wood fuel is mainly used for heating houses, hence, the total number of houses can be an explanatory variable for residential wood energy demand. A large number of houses imply more heating area, greater total demand for residential heating energy, and thus greater demand for wood energy (Hardie and Hassan, 1986).

As with other goods and services, residential wood energy demand can be associated with varying levels of personal income. Consumers tend to consume more of a “normal” good when their income increases. However, previous studies have not agreed on the relation between wood energy demand and income levels. While some studies with U.S. data have shown that higher personal income is associated with increased wood used for residential energy (e.g. Hardie and Hassan, 1986), others with Asian data have shown the reverse (e.g. Chen et al., 2006). In the later case wood energy may be identified as an “inferior” good—consumption declines as income rises (Macauley, 1989). Skog and Manthy (1989) showed that income effect on the U.S. household wood energy consumption was positive for some households but negative for others, altering with household income level. In spite of these differences, past studies did agree that income level influences wood energy consumption.

A variable measuring heating requirements (annual total heating degree days or *AHDD*) was included in the model to estimate the effect of weather on residential energy consumption (Quayle and Diaz, 1980). Homes are likely to consume more heating energy when it is colder. The *AHDD* metric is the sum of the number of degrees below 18.5 °C (65 °F) in each day of a year. Larger values of *AHDD* indicate greater annual residential heating requirements. Trend variable (t) in the model is the corresponding year of an annual observation. It was used to capture all trended factors affecting residential wood energy consumption. Examples of such time trends may include technological progress (e.g. improvements in home heating), effects of growing urbanization levels, monotonic changes in consumer taste, availability of feedstock, and access to alternative energy resources (Hunt, 2003, Lipfert and Lee, 1985).

By combining explanatory factors, residential wood energy demand may be modeled as a function of number of occupied houses (*HOU*), price of wood energy (*PW*), prices of non-wood energies (*PNW*), annual income per capita (*ICP*), annual heating degree days (*AHDD*), and a general trend variable (t). Because the wood energy price for households (*PW*) is simultaneously determined by supply and demand, it is an endogenous variable in a supply and demand system of equations. Therefore, a supply function can be used to eliminate the endogenous *PW*. With bulky volume and low value the production cost of wood energy is mainly a function of the labor required for logging, cutting, splitting, loading, unloading, and stacking (Cooke et al., 2008). Moreover, the low price of firewood relative to other wood products means that high-value wood is typically used for other products while low-value wood and residues are used to generate energy. As a case in point, it is common to find advertisements giving away firewood logs for free in U.S. urban and rural areas. A supply function for household wood energy was consequently modeled as a function of wood energy price (*PW*), wage rate (*WAGE*) and temporal variable t representing trends over time in wood energy production cost. Such a trend in the supply function could be caused by improvement in production equipment and changes in the availability of fuelwood and wood residues.

Wood energy consumption (*WOOD*) and wood energy price (*PW*) are two endogenous variables in the demand and supply functions while others are predetermined exogenous variables. As a result, the following reduced form of U.S. residential wood energy consumption was derived:

$$WOOD = f(PNW, HOU, ICP, WAGE, AHDD, t) \tag{1}$$

where *WOOD* is household wood energy consumption, $f(\cdot)$ indicates *WOOD* is a function of explanatory variables included in the parentheses. Notice that Eq. (1) eliminated the endogenous variable *PW* which eased estimation of the empirical model given that U.S. wood energy prices were not available for recent years.

As will be shown in the next section, most of the time series data used in the model exhibited unit roots and were deemed integrated and non-stationary. With non-stationary time series, the error correction model (ECM) can be used to test and estimate cointegration relations, an equilibrium relation among integrated variables over time (Granger, 1981). Past applications of ECM suggest that this model leads to more robust results than other alternatives (Amano and Norden, 1998, Asche et al., 2008, Huntington, 2010, Polemis, 2007). Examples of applications of this method in the forest and energy sectors include Toppinen (1998), Mjelde and Bessler (2009), and Song et al. (2011). To ensure positive prediction for wood energy consumption, we assumed that wood energy consumption is a log-linear function of other variables. An ECM for Eq. (1) can be expressed in log-transformed variables as in Eq. (2).

$$\begin{aligned}\Delta LWOOD_t = {} & a(LWOOD_{t-1} + b_2 LPNW_{t-1} + b_3 LHOU_{t-1} + b_4 LICP_{t-1} \\ & + b_5 LWAGE_{t-1} + b_6 t + b_0) + \textstyle\sum_{i=1}^{n} c_{1i}\Delta LWOOD_{t-i} \\ & + \textstyle\sum_{i=1}^{n} (c_{2i}\Delta LPNW_{t-i+1} + c_{3i}\Delta LHOU_{t-i+1} + c_{4i}\Delta LICP_{t-i+1} \\ & + c_{5i}\Delta LWAGE_{t-i+1}) + c_6 \Delta LAHDD_t + c_0 + \varepsilon_t\end{aligned} \tag{2}$$

Variables *LWOOD*, *LPNW*, *LHOU*, *LICP*, and *LWAGE* are log-transformed *WOOD*, *PNW*, *HOU*, *ICP*, and *WAGE* variables; a, b_0, b_2,…,

b_6, c_0, c_6, and c_{ki} (where $k=1$ to 5, and $i=1$ to n) are parameters. $\Delta LPNW_t$, $\Delta LHOU_t$, $\Delta LICP_t$, and $\Delta LWAGE_t$ (when $i=1$) are expected to have no unit root and be predetermined. All of the time series were log-transformed and tested for unit roots using both ADF and PP tests following Dickey and Fuller (1979) and Phillips and Perron (1988), respectively, with trend and intercept in the test models. First-order differences are included on the right-hand side of the equation along with their lags. The number of lags n was determined by Akaike Information Criteria (AIC). Coefficient a is for the sum of the terms in the parenthesis immediately following it and represents how fast the dependent variable is adjusted to equilibrium. The sign Δ is for the first difference (e.g. $\Delta LPNW_t = LPNW_t - LPNW_{t-1}$). ε is a random variable with mean zero. *LAHDD* is stationary (see test results in the Data section), exogenous and independent of all other variables on the right-hand side of the model, hence, it was not included in the long-run cointegration relation (Johansen, 1992, Johansen and Juselius, 1994). No lags of $\Delta LAHDD_t$ were included because individuals heat their homes according to current year's weather, not weather from prior years.

When a cointegration relation exists among variables, the sum of terms in the first set of parentheses in Eq. (2) is stationary and has a zero mean (Granger, 1981, Greene, 2002, and Johansen, 1988). Let the sum in the parentheses equal $cointEq_{t-1}$ and replace $t-1$ with t to facilitate discussion; then *LWOOD* can be expressed as in Eq. (3). This equation represents a cointegration relation among *LWOOD*, *LPNW*, *LHOU*, *LICP*, and *LWAGE* in the long-run and is also the equilibrium model representing a status in which *LWOOD* adjusts fully to the values of other variables (Maddala and Kim, 1998).

$$LWOOD_t = -b_2 LPNW_t - b_3 LHOU_t - b_4 LICP_t - b_5 LWAGE_t - b_6 t - (b_0 + b_6) + cointEq_t \quad (3)$$

The term *cointEq* is also called the equilibrium error, representing the deviation of observed values of the dependent variable *LWOOD* from the expected value at equilibrium in the same period (Greene, 2002). Since the number of houses occupied must be positively associated with the amount of energy used, the value of the coefficient for *LHOU* is expected to be positive (i.e. $b_3<0$ and $-b_3 \geq 0$). Because wood energy and non-wood energy are alternative energy sources, wood energy consumption by households is non-decreasing in *LPNW*, and its coefficient is expected to be positive. Labor price comprises the greatest cost of wood energy for residents (Cooke et al., 2008). Higher wages result in higher wood prices, consequently, higher wages should reduce wood energy consumption, *ceteris paribus*. Therefore, the coefficient for *LWAGE* in Eq. (3) is expected to be negative. The sign of the coefficient for *LICP* remains an empirical question as discussed previously. The trend effect related to time t is expected to have a negative coefficient due to the observed downward trend in residential wood energy consumption over the 1967–2009 period.

Engle and Granger (1987)[1] suggested a two-step method to test cointegration single equation models with Augmented Dickey–Fuller (ADF) test and estimated the models with ordinary least squares. MacKinnon (1994, 1996) provided modified critical values for the ADF test of this method with multiple variables (Maddala and Kim, 1998). This method first estimates the long-run cointegration relation with ordinary least squares whose residual *CointEq* is tested for stationarity with ADF statistics. The estimated equation represents a cointegration relation only if *CintEq* does not have any unit roots. The ECM model 2 can be written as in Eq. (4).

$$\begin{aligned}\Delta LWOOD_t = {} & a(CointEq_{t-1}) + \textstyle\sum_{i=1}^{n} c_{1i}\Delta LWOOD_{t-i} \\ & + \textstyle\sum_{i=1}^{n}(c_{2i}\Delta LPNW_{t-i+1} + c_{3i}\Delta LHOU_{t-i+1} + c_{4i}\Delta LICP_{t-i+1} \\ & + c_{5i}\Delta LWAGE_{t-i+1}) + c_6\Delta LAHDD_t + c_0 + \varepsilon_t.\end{aligned} \quad (4)$$

With stationary residuals (*CointEq*) of model 3, Eq. (4) can be estimated with OLS. Estimates of a reduced form model like Eqs. (3) and (4) are consistent, and in some cases are preferred (Hamilton, 1994, Jarrow and Protter, 2004). The ECM coefficients in Eq. (4) are also the short-run coefficients that represent responses of dependent variable to changes in the independent variables in the current period.

4. Data

Model variables, along with their definitions, data sources and unit root tests are presented in Table 1. Annual data for income per capita are available (*LICP*) from 1969 to 2009 while data for other variables are available from 1967 to 2009. Data values were all given in metric units. Residential prices and consumption of natural gas, electricity fuel oil, propane, and coal from Annual Energy Review 2009 were used to calculate consumption-weighted average values of non-wood energy prices. Consumer price index data from the U.S. Bureau of Labor Statistics (2010) were used to convert values of prices, wage, and income into 2008 U.S. dollars. The wage rate is the reported average payment in 2008 dollar per hour at the beginning of each year (January) for production and nonsupervisory private

Table 1
Variable descriptions, data sources and *p*-values of unit root tests.

Variables	Definitions	Sources	Unit root test *p*-values* ADF	PP
LWOOD	Log-transformed U.S. wood energy consumption in PJ (10^{15} J).	Annual Energy Review 2009 (U.S. Energy Information Administration, 2010a)	0.113	0.839
LPNW	Log-transformed price of non-wood energy in 2008 dollars per GJ (10^9 J) for households from 1972 to 2009. It is the consumption-weighted average of residential prices of natural gas, electricity, fuel oil, propane, and coal.	Annual Energy Review 2009 (U.S. Energy Information Administration, 2010a)	0.107	0.792
LHOU	Log-transformed number of occupied U.S. houses in thousand units.	U.S. Census Bureau (2010a)	0.969	0.977
LICP	Log-transformed income per capita per year in the U.S. in 2008 dollars.	U.S. Bureau of Economic Analysis (2010)	0.018	0.512
LWAGE	Log-transformed average January hourly earnings of production and nonsupervisory employees in the private sector in 2008 dollars per hour.	U.S. Bureau of Labor Statistics (2011)	0.963	0.973
LAHDD	Log-transformed annual total number of daily average degrees below 18.5 °C (65 °F). Values were converted into Celsius from Fahrenheit degrees.	Annual Energy Review 2009 (U.S. Energy Information Administration, 2010a)	0.001	0.0019

* ADF = Augmented Dickey–Fuller test. PP = Phillips–Perron test. Null hypotheses for these tests are "there is a unit root". All *p*-values of ADF and PP unit root tests for first differences of variables are less than 0.05, suggesting the first differences do not have unit roots. Consumer's Price Index (U.S. Bureau of Labor Statistics 2010) was used in converting values of price, income, and wage rate into 2008 U.S. dollars.

[1] The maximum likelihood method by Johansen (1988, 1992) and Johansen and Juselius (1990, 1992) is a method for estimating a vector ECM with more than one equation. In addition, Johansen's vector ECM does not include contemporary differences of other integrated variables since they are assumed to be endogenous (Hamilton, 1994). Because first differences of current time integrated variables are on the right-hand side of model (2), it cannot be estimated by the Johansen's method.

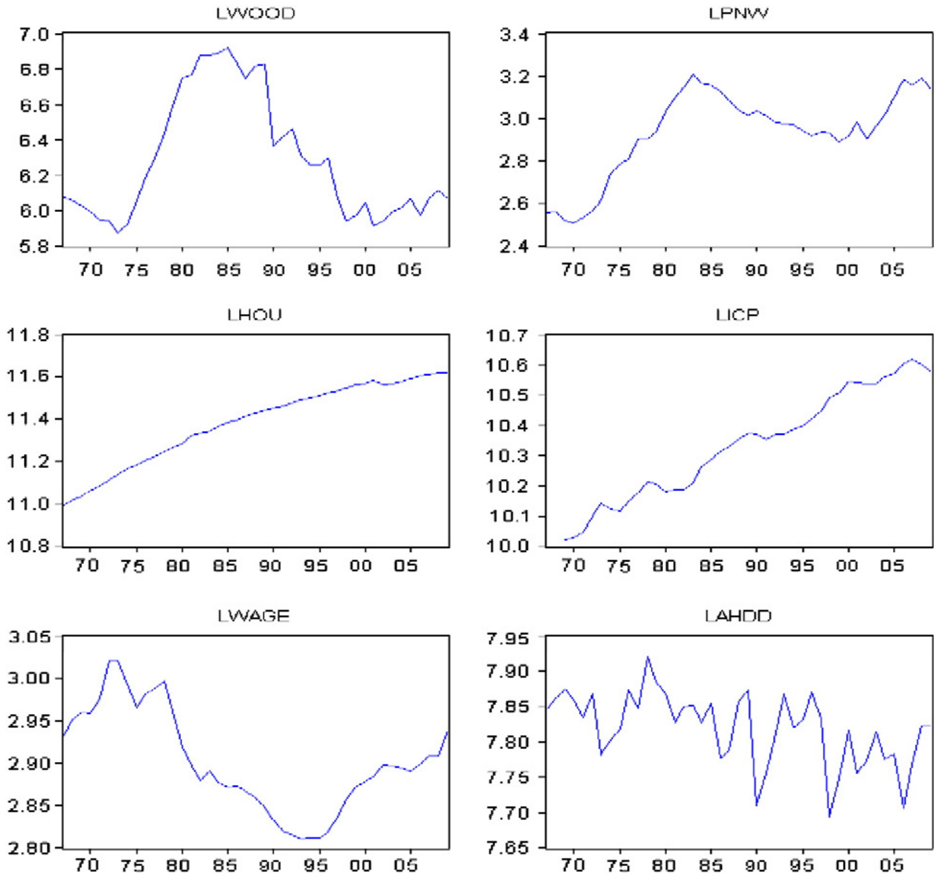

Fig. 2. Plotted log-transformed time series from 1967 to 2009, units and sources are in Table 1. Values for *LICP* in 1967–8 are not available.

employees from the Current Employment Statistics Survey (data series CES0500000008, U.S. Bureau of Labor Statistics, 2011).

The numbers of lags of the test regressions for ADF tests were determined by AIC. The *p*-values of all these tests were greater than 0.05 either by the PP or the ADF test except for *LAHDD*. The unit root hypothesis was rejected for *LAHDD* in both unit root tests (Table 1). These *p*-values suggest that all time series but *LAHDD* are suspected to have unit roots but none of the differences have unit roots. The first differences of all time series except that for *LAHDD* were also tested for unit roots to determine if they are integrated of second order.

Fig. 2 shows plotted time series from 1967 to 2009. The plot for *LWOOD* has patterns similar to those for *LPNW* and *LWAGE*. Fig. 2 also shows that the log-transformed time series of occupied homes (*LHOU*) and income per capita (*LICP*) experienced linear trends throughout the 1967–2009 period. The correlation coefficient between *LHOU* and *LICP* was greater than 0.95.

5. Results

Because trends in *LHOU* and *LICP* imply that they were linearly correlated with one another, one or two of the three variables

Table 2
Estimated results for the long-run model with excluded variables.

Variables	Estimated regression results						
	Unrestricted	*LHOU* excluded	*LICP* excluded	*t* excluded	*LHOU*, *LICP* excluded	*LHOU*, *t* excluded	*LICP*, *t* excluded
LPNW	1.82**	1.80**	1.72**	1.97**	1.82**	1.74**	2.06**
LHOU	−0.20		0.83	−2.12			−2.29**
LICP	0.94	0.84		−0.25		−1.90**	
LWAGE	−2.36**	−2.26**	−1.76**	−3.12**	−2.12**	−1.91**	−3.00**
T	−0.04**	−0.04**	−0.04**		−0.03**		
C	84.20**	84.40**	76.51**	36.28**	66.48**	26.32**	35.00**
Adjusted R^2	0.87^{MAX}	0.87^{MAX}	0.87^{MAX}	0.84	0.87^{MAX}	0.84	0.83
F-statistic	53.66	68.96	72.63	53.42	96.44^{MAX}	68.51	67.18
AIC	−1.15	−1.19	−1.23	−0.97	−1.25^{MIN}	−0.96	−0.94
SC	−0.90	−0.99	−1.03	−0.76	−1.09^{MIN}	−0.80	−0.78
HQC	−1.06	−1.12	−1.16	−0.90	−1.19^{MIN}	−0.90	−0.88
p-value of cointegration tests. H_0: no cointegration							
PP					<0.01		
ADF					0.03		

**: Significant at 1% level. ^{MAX}: maximum value. ^{MIN}: minimum value.
AIC = Akaike Information Criteria; SC = Schwarz Criterion (SC); HQC = Hannan–Quinn Criterion; PP = Phillips–Perron test; ADF = Augmented Dickey–Fuller test.

LHOU, *LICP*, and t could be dropped from the model. If one or two of the three variables were excluded, the remaining coefficients would incorporate their effects. To use as much of the available information as possible, the residential wood energy consumption model was estimated with annual data from 1969 to 2009 when *LICP* was included and from 1967 to 2009 when *LICP* was excluded. The estimated coefficients of a reduced version of Eq. (3) after excluding one or two of these three variables are shown in Table 2.

The estimated model without *LHOU* and *LICP* had the greatest adjusted R^2 and F-statistics and minimum values of AIC, Schwarz Criterion, and Hannan–Quinn Criterion that imply better model fitness (Greene, 2002). Dropping variables *LHOU* and *LICP* improved the estimation of the long-run model (Eq. (3)). Moreover, the estimated coefficient values of *LPNW*, *LWAGE*, and t were relatively stable with consistent signs across the different restricted models, while those of *LHOU* and *LICP* were not. The estimated coefficients of *LPNW*, *LWAGE*, and t were significant whenever those variables were included, while those of *LHOU* and *LICP* were significant when only one of them and the trend t were excluded (see first and second columns of coefficients in Table 2 from the right). When *LHOU* and *LICP* were excluded their effects could not be estimated directly, but their effect was captured in the temporal trend. The long-run estimated model without *LHOU* and *LICP* was reduced to:

$$LWOOD_t = 1.82LPNW_t - 2.12LWAGE_t - 0.03\,t + 66.48 + cointEq_t. \quad (5)$$

The ADF t-statistic for the residual of this estimation was -4.73. The critical value for the cointegration test is a function of the number of integrated variables and the number of observations (Maddala and Kim, 1998). The critical value calculated following MacKinnon (1996) for testing residuals from the estimation with three integrated variables, 43 observations, a trend, and an intercept was -4.66 at the type-I error 0.03 level. Thus, the hypothesis that no cointegration relations exist was rejected. This result implies that the estimated Eq. (5) is a cointegration relation among *LWOOD*, *LPNW*, and *LWAGE*. The fitted values and residuals suggest that most of the changes in the U.S. residential wood energy consumption have been captured by the estimated model as visually depicted in Fig. 3.

Because variables are log-transformed, the estimated coefficients of *LPNW* and *LWAGE* in Eq. (5) represent elasticities of the U.S. residential wood energy consumption. The estimated coefficients of these two variables suggest that residential wood energy consumption changed 1.82% and -2.12% as a result of a 1% increment in non-wood energy price and wage rate, respectively. The estimated coefficient for t in Eq. (5) suggests that the U.S. residential wood energy consumption decreased at an average of 3% every year *ceteris paribus*.

The ADF test for the difference of integrated variables $\Delta LPNW$, $\Delta LHOU$, $\Delta LICP$, and $\Delta LWAGE$ indicates that they have no unit root, meeting the assumption for an ECM model (footnotes of Table 1).

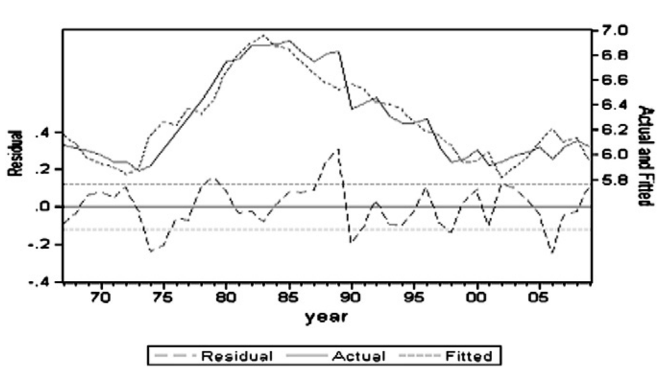

Fig. 3. Plotted, actual and fitted values of *LWOOD* and residuals (equilibrium errors) of the estimated long-run model.

Eq. (4) was estimated with up to four lags. A backward step-wise variable selection was performed to simplify the model (Lhabitant, 2004). The variable with the largest p-value was excluded, and then the model was re-estimated. This exclusion and re-estimation procedure was repeated until all remaining coefficients were significant at 5% type-I error level. The variables $\Delta LHOU_t$, ΔICP_t and their lags have coefficients that were statistically insignificant and were dropped from the ECM. Eq. (6) is the estimated ECM with significant coefficients. The Breusch–Godfrey serial correlation test with 10 lags and the Ljung–Box Q test for each of the first ten lags cannot reject the hypotheses of no autocorrelation in the residuals, thus, autocorrelation is insignificant. An autoregressive conditional heteroskedasticity (ARCH) test with lags 1 or 2 showed ARCH to be statistically insignificant. The fitted ECM short-run model is as follows:

$$\begin{aligned}\Delta LWOOD_t = &-0.30(CointEq_{t-1}) + 0.24\,\Delta LWOOD_{t-1} + 0.31\Delta LWOOD_{t-3}\\ &-1.53\Delta LWAGE_t + 1.12\Delta LAHDD_t + \varepsilon_t.\end{aligned} \quad (6)$$

All the estimated coefficients had the expected signs. The coefficient of $CointEq_{t-1}$ represents a 30% adjustment each year to the long-run equilibrium of log-transformed wood energy consumption determined by the values of variables in the previous year. The first difference of log-transformed price of non-wood energy PNW_t and its lags were excluded from Eq. (6) because estimated coefficients were not statistically significant. These exclusions imply that residential wood energy consumption does not respond significantly to these variables in the short-run (current year). The estimated coefficients of $\Delta LWAGE$ and $\Delta LAHDD$ represent changes in percent of wood energy consumption as a result of one percent change in values of the two variables. Thus, model results suggest that for every 1% annual increment in wage rates the current year wood energy consumption dropped 1.53%, and for every 1% annual increment in *AHDD*, compared to the last year, the current year consumption increased 1.12%. The positive coefficients of the lagged dependent variables in Eq. (6) represent the autoregression of residential wood energy consumption. For a 1% change in residential wood energy consumption in the previous year it will continue to change 0.24% in the current year, *ceteris paribus*. The coefficient 0.31 can be explained similarly.

Eq. (5) represents an equilibrium relation among *LWOOD* on the left-hand side and other integrated variables on the right-hand side in the long-run. The estimated ECM (Eq. (6)) represents the current year response of residential wood energy consumption to changes in variables and the equilibrium error. The estimated ECM is the data generation function for *LWOOD* (Granger, 1981).

6. Discussion

Table 2 shows that when two of the three variables *LHOU*, *LICP* and t were excluded, the third one had a significant estimated coefficient. Since *LHOU* and *LICP* are linearly correlated, the estimated coefficient of t captured the combined effect of the three variables. Effects of number of occupied homes and income per capital cannot be estimated separately. As previous studies have suggested, the coefficient of t also captured technological progress, monotonic changes in consumer's perception of renewable energy, trends in the availability of feedstock, increasing access to alternative energies, and urbanization.

The estimated coefficient of the price of non-wood-energy was greater than 1.0 in the long-run (Eq. (5)), while that of the same variable was insignificant in the short-run (Eq. (6)). This result implies that U.S. residential wood energy was sensitive to changes in non-wood energy prices in the long-run, but not to such changes in the current year. A possible explanation for this finding is that homeowners were reluctant to change heating in the short term. With estimated adjustment coefficient of -0.30 (Eq. (5)), our model

Table 3
Changes in values of variables and their estimated effects on U.S. residential wood energy consumption based on the estimated long-run coefficients.

Variable	Coefficients	1967–2009		2000–2009	
		Change in values	Effects on *LWOOD*	Change in values	Effects on *LWOOD*
LPNW	1.82	0.5808	1.06	0.2184	0.40
LWAGE	−2.12	0.0058	−0.01	0.0589	−0.12
T	−0.03	42	−1.26	9	−0.27
Total			−0.21		0.01

suggests the U.S. residents would adjust their wood energy consumption to fully respond to a change in non-wood energy price over time.

The absolute values of estimated coefficients for the average hourly earnings of employees in the U.S. were greater than 1.0 in both the equilibrium and ECM short-run models. The negative and significant coefficient of the wage rate suggests that U.S. residential wood energy consumption would decrease 1.53% for a 1% increment in the wage rate within the current year, and would eventually decrease a total of 2.12% in the long-run.

The estimated long-run coefficients and historical changes in the price of non-wood energy and the wage rate can explain changes in wood energy consumption over time. Rising fossil fuel prices and declining wage rates between 1973 and 1983 increased total residential wood energy consumption during these years. Contraction of non-wood energy price since 1984 first showed its effect on residential wood energy consumption in 1986 (Figs. 1 and 3). The price of non-wood energy reached its lowest point in 1999 and its consequent effect was not observed until 2001 when residential wood energy consumption reached its lowest level. In the last decade, while the ascending price of non-wood energy had a positive effect on U.S. residential wood energy consumption, rising wage rates had negative effects on residential wood energy consumption.

To analyze the total effect of explanatory variables, we analyzed changes in each of these variables individually and then used the estimated long-run coefficients to evaluate the joint effects of these changes (Table 3). We concentrated our analysis on two time periods. First, we evaluated total effects of explanatory variables between 1967 and 2009 to include all our observations and then, we concentrated on the 2000–2009 period to better explore changes experienced during the last decade. The estimated total effects of changes in non-wood energy price, wage rate, and temporal trend on *LWOOD* from 1967 to 2009 were 1.06, −0.01, and −1.26, respectively. Compared to the effects of non-wood energy price and the time trend, the total estimated effect of wage rate change in the 42-year period was negligible. The nearly even levels of U.S. real wage rate in 1967 and 2009 explained the negligible effect of this variable over this period (Fig. 1). The historical decline of U.S. residential wood energy consumption had been a result of the time trend (and its associated factors) rather than that of higher wage rates. The long term trend of increasing prices for non-wood energy appears to have slowed the rate of decline in U.S. residential wood energy consumption.

Fig. 2 showed that the period from 2000 to 2009 was characterized by rapidly increasing non-wood energy price and wage rate. The estimated effects of changes in non-wood energy price, wage rate, and time for this 9-year period on log-transformed wood energy consumption were 0.40, −0.12, and −0.27, respectively (Table 3). Despite the rapid increase of non-wood energy price and its positive effect on residential wood energy consumption, the net effect on *LWOOD* of increasing non-wood energy prices, rising wage rate, and the temporal trend was only 0.01. Consequently, the increasing price for non-wood energy from 2000 to 2009 did not result in greater wood energy consumption.

The composite non-wood energy price in the U.S. had a tendency to increase in the long-run as shown in Fig. 2. But the declining trend effect in U.S. residential wood energy consumption has been larger than the positive effect associated with the increasing non-wood energy price. Thus, U.S. residential wood energy consumption is likely to continue to decline in the long-run as it did in the last 60 years if no further action is taken to promote its use in the future.

However, residential wood energy consumption has the potential to increase if conversion efficiency is improved by using available high-efficiency wood heating equipment. Technical improvements can make residential wood energy more cost competitive. Traditional fireplaces that most homes are equipped with today have a poor heating efficiency—as low as 10% (U.S. Department of Energy, 2010, U.S. Environmental Protection Agency, 2011a, 2011b). But the heating efficiency of a modern stove or fireplace insert is as high as 70%. Greater efficiency can result in lower cost of home heating using wood. Historically wood fuel has been inexpensive compared to non-wood energy (Koning and Skog, 1987) and remains inexpensive today because the real labor cost per hour has changed little over 42 years. Moreover, U.S. prices of air-dried and home-delivered firewood advertised in the worldwide web ranged from being free to $83/m^3$ ($300 per cord) in recent years. A common price of U.S. firewood advertised online in the winter of 2009 was about $41/m^3$ ($150 per cord), equivalent to US$6.4/GJ (US$6.8 per million Btu). Even when heating efficiency is as low as 55%, the cost of wood energy heating ($11.7/GJ) (Forest Product Laboratory, 2004) is still lower than electricity, priced at $31.6/GJ ($33.3 per million Btu), and natural gas, priced at $12.6/GJ ($13.3 per million Btu) (U.S. Energy Information Administration, 2010c).

Our estimated coefficient for non-wood energy price also implies that decreasing the relative cost of wood energy encourages wood energy use by U.S. residents. Previous studies have shown that lowering wood energy price encouraged residential wood energy consumption as any normal goods do (Skog and Manthy, 1989, Skog and Watterson, 1984). These results suggest that public policies increasing wood energy competitiveness by reducing wood energy cost relative to non-wood energy could effectively promote wood energy use by U.S. residents.

Public policy (e.g. through tax incentives) can have an important role to play promoting the adoption of highly-efficient residential wood heating equipment. However, as determined in our analysis, because residential wood energy consumption responds slowly to changes, responses to public policy may not be observed until at least two years after a new policy is instituted but its effect could last multiple years. The fact that U.S. households may not react immediately to a changes in policy also bring up the issue about the importance of a stable and comprehensive energy agenda. It will not be until there is a consistent set of policies that provide sufficient and long-lasting incentives to households that these will decide to invest in new forms of home heating systems such as biomass stoves.

While we could infer from our model that effect of incentives cannot be observed in the short term, our model was not able to capture the effect of recently adopted public policies. For example, the federal biomass stove tax credit became available in 2006, but with only four annual observations from 2006 to 2009 it was not possible to estimate its effect econometrically. We deem the biomass stove tax credit presented no comparative advantage for wood energy over non-wood energy, because similar tax credits were also available for oil heating equipment over the same time period (i.e. there was no relative improvement in wood energy price competitiveness). In addition, the credit limit has been reduced to $500 for an eligible stove in 2011 from $1500 in the previous year (DSIRE, 2011), and the smaller incentive presumably reduced the likelihood of households adopting wood heating. Therefore, it is understandable that U.S. residential wood energy consumption has not changed much in recent years and it is not likely to change much in the near future (Fig. 1). Should non-wood energy price stop rising, as it did in the 1990s, we may even observe a drop in residential wood energy consumption.

It is important to mention that while our study investigated changes in residential wood energy consumption over time at the national level, it was not suited for capturing differences in consumption patterns between rural and urban areas as shown in previous studies (e.g. Skog and Manthy, 1989). Residential energy consumption information used in this study does not lend itself to a regional analysis because of lack of time series data corresponding to urban/rural areas (i.e. data is aggregated at the U.S level). To address this shortcoming the authors are engaged in a cross sectional study of household wood energy consumption focusing on regional and urban/rural variations using information from the RECS. Results from the latter will complement the findings presented in this paper.

7. Conclusion

This research found that the composite non-wood energy price was positively associated with U.S. residential wood energy consumption in the long-run with elasticity 1.82. Wage rate was negatively associated with wood energy consumption in both long- and short-run with elasticities of −2.12 and −1.53, respectively. The estimated trend (t) in residential wood energy consumption was significantly negative, about −3% per year. Effects of the number of occupied homes and income could not be estimated separately but were implicitly included in the temporal trend.

Although the marginal effect of composite non-wood energy price on residential wood energy consumption was significant in the long-run, it had no significant effect in the current year (short-run). Residential wood energy consumption takes about two years to respond to a change in non-wood energy price and it takes multiple years to see the total effect of a price change.

The total empirical positive effect of the increasing non-wood energy price from 1967 to 2009 was large but was offset by the negative trend representing effects of trended variables, technological improvement, changes in resources, availability of alternative energy, public perception toward renewable energy, urbanization and other variables that were not included in the model but followed a monotonic trend over this period. The effect of wage rate on consumption was negligible from 1967 to 2009 because the change in U.S. average wage rate during this period was relatively small. The combined effects of gradually rising wage rates and the time trend offset the effect of an increasing non-wood energy price in the last decade and resulted in moderate changes in U.S. residential wood energy consumption.

If the wage rate and non-wood energy price continue rising at the pace observed in recent years, we can expect U.S. wood energy consumption to change little in the near future. The long-run relationships identified by our model suggest U.S. residential wood energy consumption is likely to decline if non-wood energy price stops rising as fast as it did in the last decade. However, wood energy can be competitive at the household level if improved heating technologies are installed. U.S. public policies supporting utilization of high-efficiency stoves could be instrumental in promoting growth in wood energy consumption by lowering the cost for producing a unit of heating energy. The model in this study was not able to detect the effect of change in equipment subsidy on wood energy use because of lack of a sufficient number of observations. The stability of public policy to promote residential wood energy use is critical to encourage homes to use greater wood energy. Households are slow to respond to price changes which will require a long-term public commitment to the utilization of wood fuels.

Acknowledgements

This research was partly supported by the United States Department of Agriculture, Forest Service through agreement number 09-JV-11242311-008. The authors thank two anonymous referees for their insightful comments. Any remaining errors are the responsibility of the authors.

References

Aguilar, F.X., Garrett, H.E., 2009. Perspectives of woody biomass for energy: survey of state foresters, state energy biomass contacts, and national council of forestry association executives. J. For. 297–306 September.

Aguilar, F.X., Saunders, A., 2009. Policy instruments promoting wood to energy uses in the continental United States. J. For. 35 (2), 73–79.

Aguilar, F.X., Song, N., Shifley, S.R., 2011. Review of consumption trends and public policies promoting woody biomass as an energy feedstock in the U.S. J. Biomass Bioenerg 35, 3708–3718.

Alabama Department of Revenue, 2005. Wood-burning heating system deduction code of Ala.§ 40-18-15. Available online at www.legislature.state.al.us/CodeofAlabama/1975/40-18-15.htm2005last accessed Oct. 24, 2008.

Amano, R.A., Norden, S.V., 1998. Oil prices and the rise and fall of the US real exchange rate. J. Int. Money Finance 17, 299–316.

Arizona Department of Commerce, 1994. Partnership income tax return, ARS § 43–1027. Available online at www.revenue.state.az.us/forms/2002/165i.pdf. last accessed Oct. 24, 2008.

Asche, F., Kumbhakar, S.C., Tveteras, R., 2008. A dynamic profit function with adjustment costs for outputs. Empire Economics 35, 379–393.

Butler, B.J., 2010. Forest land Owners of the United States. Gen. Tech. Rep.NRS-27. USDA Forest Service, Northern Research Station, Newtown Square, PA, USA. 72 pp.

Cannell, M.G.R., 2003. Carbon sequestration and biomass energy offset: theoretical, potential and achievable capacities globally, in Europe and the UK. Biomass Bioenergy 24 (2), 97–116.

Chen, L., Heerink, N., Berg, M., 2006. Energy consumption in rural China: a household model for three villages in Jiangxi Province. Ecol. Econ. 58 (2), 407–420.

Cooke, P., Köhlin, G., Hyde, W.F., 2008. Fuelwood, forests and community management—evidence from household studies. Environ. Dev. Econ. 13, 103–135.

Dickey, D.A., Fuller, W.A., 1979. Distribution of the estimators for autoregressive time series with a unit root. J. Am. Stat. Assoc. 74, 427–431.

DSIRE, 2011. Incentives/policies for renewable energyOnline from http://www.dsireusa.org2011Accessed on March. 26, 2011.

Energy Information Administration, U.S., 2010c. Heating fuel comparison calculator. Available at www.eia.doe.gov/neic/experts/heatcalc.xls. Accessed on March 10 2010.

Engle, R.F., Granger, C.W.J., 1987. Co-integration and error-correction: representation, estimation and testing. Econometrica 55, 251–276.

Forest Product Laboratory, U.S., 2004. Techline: fuel value calculator. Online available at http://www.fpl.fs.fed.us/documnts/techline/fuel-value-calculator.pdf2004Accessed on May 2010.

Granger, C.W.J., 1981. Some properties of time series data and their use in econometric model specification. J. Econometrics 16, 121–130.

Greene, W.H., 2002. Econometric Analysis, Fifth Edition. Prentice Hall, Upper Saddle River New Jersey.

Hamilton, J.D., 1994. Time Series Analysis. Princeton University Press, Princeton, New Jersey.

Hardie, I.W., Hassan, A.A., 1986. An econonmetric analysis of residential demand for fuelwood in the United States 180–1981. Forest Sci. 32 (4), 1001–1005.

Howard, J.L., Westby, R., 2009. U.S. forest products annual market review and prospects, 2005–2008. Research Note FPL-RN-0313. Forest Products Laboratory. USDA Forest Service.

Hunt, L.C., 2003. Energy in a Competitive Market: Essays in Honour of Colin Robinson. Edward Elgar Publishing, Cheltenham, UK. 256 pp.

Huntington, H.G., 2010. Short- and long-run adjustments in U.S. petroleum consumption. Energy Economics 32, 63–72.

International Energy Agency, 2007. IEA energy technology essentials ETE03: biomass for power generation and CHPOnline at: http://www.iea.org/techno/essentials3.pdf2007Accessed on Jan. 30, 2011.

Jarrow, R.A., Protter, P., 2004. Structural versus reduced form models: a new information based perspective. J. Invest. Manag. 2, 1–10.

Johansen, S., 1988. Statistical analysis of cointegration vectors. J. Econ. Dynamic. Control 12, 231–254.

Johansen, S., 1992. Cointegration in partial systems and the efficiency of single-equation analysis. J. Econ. 52, 389–402.

Johansen, S., Juselius, K., 1990. The maximum likelihood estimation and inference on cointegration with application to demand for money. Oxf. Bull. Econ. Stat. 52, 169–210.

Johansen, S., Juselius, K., 1992. Testing structural hypothesis in a multivariate cointegration analysis of the PPP and the UIP for UK. J. Econ. 53, 211–244.

Johansen, S., Juselius, K., 1994. Identification of the long-run and short-run structure: an application to the ISLM model. J. Econometrics 63, 7–36.

Koning, J.W., Skog, K.E., 1987. Use of wood energy in the United States—an opportunity. Biomass 12, 27–36.

Lhabitant, F.S., 2004. Hedge funds: quantitative insights. John Wiley & Sons Inc, Hoboken, NJ USA, pp. 173–174.

Lipfert, F.W., Lee, J., 1985. Air pollution implications of increasing residential firewood use. Energy 10, 17–33.

Macauley, M., 1989. Fuelwood use in urban areas: a case study of Raipur, India. Energy Journal 10 (3), 157–180 Retrieved from EconLit database.

MacKinnon, J.G., 1994. Approximate asymptotic distribution functions for unit-root and cointegration tests. J. Bus. Econ. Stat. 12, 167–176.

MacKinnon, J.G., 1996. Numerical distribution functions for unit root and cointegration tests The program for calculating the critical values is available at: J. Appl. Econ. 11, 601–618http://www.econ.queensu.ca/faculty/mackinnon/numdist.

Maddala, G.S., Kim, I.M., 1998. Unit Roots, Conintegraion, and Structural Change. Cambridge University Press, New York, NY.

Mjelde, J.W., Bessler, D.A., 2009. Market integration among electricity markets and their major fuel source markets. Energy Economics 31, 482–491.

Perlack, D.R., Wright, L.L., Turhollow, A.F., Graham, R.L., Stocks, B.J., Donald, C.E., 2005. Biomass as feedstock for a bioenergy and bioproducts industry: the technical feasibility of a billion-ton annual supply. Online available at http://www1.eere.energy.gov/biomass/pdfs/final_billionton_vision_report2.pdf. Accessed on Dec. 10, 2009.

Phillips, P.C.B., Perron, P., 1988. Testing for unit root in time series regression. Biometrika 75, 335–346.

Polemis, M.L., 2007. Modeling industrial energy demand in Greece using cointegration techniques. Energ. Pol. 35, 4039–4050.

Quayle, R.G., Diaz, H.F., 1980. Heating degree day data applied to residential heating energy consumption. J. Appl. Meteorol. 19 (3), 241–246.

Schlamadinger, B., Spitzer, J., Kohlmaier, G.H., Lüdeke, M., 1995. Carbon balance of bioenergy from logging residues. Biomass Bioenergy 8 (4), 221–234.

Schwaiger, H., Schlamadinger, B., 1998. The potential of fuelwood to reduce greenhouse gas emissions in Europe. Biomass Bioenergy 15 (4–5), 369–377.

Skog, K.E., 1993. Projected wood energy impact on U.S. forest wood resources. Proceedings of 1st. Biomass Conference of the Americas: Energy, Environment, Agriculture, and Industry, Burlington, VT, Golden, CO, U.S., Vol. 1, pp. 18–32.

Skog, K.E., Manthy, R.S., 1989. Fuel wood use in U.S. counties, Natural Resource Research Report No. 486. Michigan State University Agricultural Experiment Station, East Lansing, MI, USA. 35 pp.

Skog, K.E., Watterson, I.A., 1984. Residential fuel wood use in the United States. J. For. 82 (12), 742–747.

Song, N., Chang, J., Aguilar, F.X., 2011. U.S. softwood lumber demand and supply estimation using cointegration in a system of dynamic simultaneous equations. J. For. Econ. 17, 19–33.

Song, N., Aguilar, F.X., Shifley, S., Goerndt, M., 2012. Factors Affecting Wood Energy Consumption by U.S. Households. Energy Economics 34, 389–397.

State of Maryland, Maryland Tax—General Section 11–207. 2005. Available online at http://law.justia.com/maryland/codes/gtg/11-207.html; last accessed Oct. 24, 2008.

Toppinen, A., 1998. Incorporating cointegration relations in a short-run model of the Finnish sawlog market. Can. J. For. Res. 28, 291–298.

U.S. Bureau of Economic Analysis, 2010. State annual personal income. Online at: http://www.bea.gov/regional/spi/default.cfm?selTable=summary. Accessed on Dec. 16, 2010.

U.S. Bureau of Labor Statistics, 2010. Consumer price index. Online at: http://bls.gov/cpi/. Accessed on Dec. 16, 2010.

U.S. Bureau of Labor Statistics, 2011. Employment, hours, and earnings from the current employment statistics survey (National). Online at: http://data.bls.gov:8080/PDQ/outside.jsp?survey=ce. accessed on Jan. 16, 2011.

U.S. Census Bureau, 2010a. Table 7. Estimates of the total housing inventory for the United States: 1965 to present. Online at: http://www.census.gov/hhes/www/housing/hvs/historic/index.html. Accessed on Dec 12, 2010.

U.S. Census Bureau, 2010b. Table 4. Population:1790 to1990. Online at: http://www.census.gov/population/www/censusdata/files/table-4.pdf. Accessed on Jan 30, 2011.

U.S. Census Bureau, 2010c. The 2010 statistical abstract. Available at: The National Data Book. http://www.census.gov/compendia/statab/past_years.html. Accessed on Feb 10, 2011.

U.S. Department of Energy, 2010. Wood and pellet heating. Online at: http://www.energysavers.gov/your_home/space_heating_cooling/index.cfm/mytopic=12570. Accessed on Jan 5, 2011.

U.S. Department of Energy, 2011. Industial technologies program: powering progress in combined heat and power (CHP). Online from http://www1.eere.energy.gov/industry/distributedenergy/pdfs/itp_chp.pdf. Accessed March, 2011.

U.S. Energy Information Administration, 1999. A look at residential energy consumption in 1997. DOE/EIA-0632 (97). Online at: http://www.eia.doe.gov/emeu/recs/pubs.html. accessed on July 28, 2010.

U.S. Energy Information Administration, 2000. Changes in energy usage in residential housing unit. Available at http://www.eia.doe.gov/emeu/recs/recs97/decade.html#totcons3. Accessed on May 30, 2010.

U.S. Energy Information Administration, 2010a. Annual energy review 2009. Online at http://www.eia.doe.gov/emeu/aer/pdf/aer.pdf. Accessed on Jan. 10, 2011.

U.S. Energy Information Administration, 2010b. Definitions of energy-use sectors and related terms. Available at http://www.eia.doe.gov/neic/datadefinitions/sectors25B1.htm. Accessed on Feb. 8, 2010.

U.S. Energy Information Administration, 2010c. Residential energy consumption survey, home energy uses and costs. Available at www.eia.doe.gov/emeu/recs/. Accessed on March 10 2010.

U.S. Environmental Protection Agency, 2011a. Consumers—choosing appliances—choosing the right fireplace. On line at: http://www.epa.gov/burnwise/fireplaces.html. accessed on Feb 10, 2011.

U.S. Environmental Protection Agency, 2011b. Regulation of fuels and fuel additives: 2011 renewable fuel standards; final rule. 40 Code of Federal Regulations Part 80: 76790–76830.

Warsco, K., 1994. Conventional fuel displacement by residential wood use. For. Prod. J. 44 (1), 68–74.