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Economic and policy factors driving adoption of institutional woody biomass heating systems in the U.S.☆

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ABSTRACT

Abundant stocks of woody biomass that are associated with active forest management can be used as fuel for bioenergy in many applications. Though factors driving large-scale biomass use in industrial settings have been studied extensively, small-scale biomass combustion systems commonly used by institutions for heating have received less attention. A zero inflated negative binomial (ZINB) model is employed to identify economic and policy factors favorable to installation and operation of these systems. This allows us to determine the effectiveness of existing policies and identify locations where conditions offer the greatest potential for additional promotion of biomass use. Adoption is driven by heating needs, fossil fuel prices, and proximity to woody biomass resources, specifically logging residues, National Forests, and fuel treatments under the National Fire Plan.

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1. Introduction

Active forest management is associated with abundant stocks of woody biomass that can be used as fuel and feedstocks for bioenergy and bioproducts (Gregg and Smith, 2010; Rummer et al., 2005; U.S. DOE, 2011). Many private and public facilities in the United States (U.S.) currently use woody biomass as fuel in decentralized heating systems and cite a variety of benefits related to biomass heat, including on-site disposal of manufacturing byproducts, lower fuel costs, substitution of fossil fuel with local renewable fuels, reduced emissions, and support of local forest management and forest industry (Nicholls et al., 2008; Wood and Rowley, 2011).

The purpose of this study is to expand the knowledge of economic and policy factors that influence the installation and operation of these systems, with the goal of informing the adoption of institutional biomass heating, which is currently in a period of expansion. The effects of state-level public policy are explicitly quantified, while federal policy is quantified implicitly through examination of federal land ownership and associated management practices, including wildfire risk mitigation through the National Fire Plan (NFP). In addition, this analysis includes variables associated with climate, energy prices, affluence, population, transportation infrastructure, and regional variation. Results provide institutions with a deeper understanding of the factors favorable to facility siting that can be used when considering the installation of new heating systems. This research also provides policy makers with knowledge about what effects, if any, different policies have on adoption, and identifies specific locations where efforts to stimulate new installations are likely to be effective.

Additional context is needed to understand why, after two centuries of using biomass for heat in an industrialized economy in the U.S., these

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relationships are not already well understood and widely known. Section 2 reviews literature by discussing the history, status and drivers of institutional biomass use, and Section 3 provides a discussion of methods, data sources and their theoretical justification, followed by model diagnostics. Section 4 presents the results, followed by a discussion in Section 5, and conclusions in Section 6.

2. Status and drivers of institutional biomass use

2.1. Modern use of biomass energy

Though it constitutes a small proportion of total energy consumption and production, biomass currently accounts for about one quarter of the total primary non-fossil energy produced in the U.S. (U.S. EIA, 2014; U.S. DOE, 2016) and use has been increasing since 2002 (U.S. EIA, 2005). Modern use of biomass fuels in industrialized countries is dominated by industrial co-generation of heat and power, private residential heating, and district heat and electric power generation using advanced biomass combustion, gasification and pyrolysis technologies (Bridgewater et al., 2002; Dong et al., 2009; McKendry, 2002; Wood and Rowley, 2011). Biomass collected from forests falls into four primary categories: 1) fuelwood, which is wood cut specifically for use as fuel, 2) logging residues, which are the tops, limbs, foliage and sometimes stumps of trees cut for roundwood products, 3) mill residues, which are the wood and bark byproducts generated by primary mills during the production of primary wood products, and 4) trees cut or otherwise killed by silvicultural operations such as pre-commercial and fuel reduction thinning (USDA Forest Service, 2009). These biomass sources and agricultural crop residues are now complemented by dedicated biomass energy crops including both woody and herbaceous species grown specifically for energy use.

Many industrialized countries around the world are actively setting renewable energy goals that can, in part, be met by using biomass for energy. Some nations in the European Union (E.U.) have embraced policies promoting biomass fuels as a means to reduce foreign energy and fuel imports, while meeting emissions standards set within the E.U. (Dong et al., 2009; Qian and McDow, 2013). In the U.S., the federal government and some state and local governments have also been aggressively pursuing policies that encourage the use of biomass for energy. In particular, forest biomass use has been promoted as a mechanism to improve forest conditions (Dykstra et al., 2008; Noss et al., 2006), reduce greenhouse gas emissions (Malmsheimer et al., 2008; Nicholls et al., 2006), and ensure affordable energy is available in the future. In fire-prone regions, the link between biomass energy and improving forest conditions is closely connected to biomass harvest from treatments implemented for fuel reduction and forest restoration, which remove primarily dead, dying and subdominant trees to reduce the intensity of wildfire when it occurs (Evans and Finkral, 2009).

When energy from woody biomass is used primarily as a mechanism to reduce greenhouse gas emissions, it is important to acknowledge both the conditions under which net reductions are likely to occur, and also the potential tradeoffs involved in substituting woody biomass for other fuel and energy options. Woody biomass energy systems are more likely to result in net greenhouse gas emission reductions when replacing carbon intensive fossil fuel systems in an efficient conversion pathway with biomass waste or logging byproducts rather than whole green trees, especially if woody biomass is collected from land that is close to the facility, remains in forested land use, and has high primary productivity (EEA, 2013). If such woody biomass is otherwise likely to be burned for disposal, which is common practice in many parts of the world, additional reductions, especially in methane, are possible (Loeffler and Anderson, 2014). However, even under the most favorable circumstances, woody biomass energy is not without tradeoffs. For example, negative impacts on local air quality may be higher than those of some fossil fuels, especially natural gas, because even highly efficient systems produce detrimental air emissions of fine particles (PM10) and black carbon (Obaidullah et al., 2012). Effects of biomass harvesting on soil properties, including productivity, carbon storage and biodiversity, is also a concern because harvesting can remove nutrients from the site and degrade soils through compaction and erosion (Nave et al., 2010; Page-Dumroese et al., 2010).

Given these potential benefits and concerns, researchers have increased their attention to the economic, policy, ecological and emissions aspects of increased forest biomass use. Several studies have focused on biomass in the electric power sector in the U.S., identifying counties with high estimated potential for co-firing biomass with coal and assessing the influence of economic incentives on adoption (Aguilar et al., 2012; Goerndt et al., 2013), or analyzing the performance and economic viability of relatively new decentralized energy systems (Bridgewater et al., 2002; Wood and Rowley, 2011; Salomon et al., 2011). Others have examined efficient carbon dioxide (CO2) emission reductions achieved when retrofitting small-scale fossil-fuel combined heat and power systems (CHP) to incorporate woody biomass (Pavlas et al., 2006), the optimization of incorporating biomass into large-scale fossil-fuel CHP plants (Tous et al., 2011), or the sustainability of rural district heating in fire-prone communities (Blanco et al., 2015). Less is known about the determinants of adoption in the commercial heating sector, at least partly because the drivers are closely tied to those affecting the electric power sector after 1990 (Aguilar et al., 2011). This study expands the knowledge of the commercial sector by evaluating economic and policy factors that are hypothesized to influence the institutional adoption of decentralized woody biomass heating systems in the U.S.

2.2. The current state of institutional biomass heating

According to some technology developers, public officials and researchers, many small commercial and institutional facilities are ideally suited for cost competitive adoption of woody biomass heating systems under the appropriate market conditions and financial incentives. This includes facilities that are located near forested land or have locally available biomass, and are currently using high priced natural gas, propane or fuel oil as their primary heat source (Galik et al., 2009; Skog et al., 2006; U.S. GAO, 2005). However, it can be more difficult for biomass to be cost competitive when fossil fuels are inexpensive, especially for district heating and power applications.

In contrast to district heating systems, power plants and large industrial boilers, the heat output of small-scale, decentralized biomass-fueled combustion heating systems ranges between one and ten million British thermal units. These systems, referred to as “biomass heating systems” in this paper, rarely include electricity generating capabilities, but can be equipped with automatic fuel handling and feeding systems to enhance their energy and labor efficiency (Maker, 2004). Fuel for these systems is most often pellets, chips, ground biomass, or fuelwood (potentially including the bole, limbs, bark and needles) from trees grown in a forest or plantation, but can also be derived from herbaceous energy crops, wood waste, or byproducts of wood product manufacturing.

Nationwide, in 2014 there were 401 known biomass heating systems installed in U.S. institutions like schools, hospitals, government facilities, prisons, military bases, and other public buildings (Fig. 1) (W2E, 2014). In general, it is recognized that public and private institutions in some regions have been more receptive to using biomass heating systems. According to the Wood2Energy database, these regions include the Northeast states, the Lakes States, and Northwest states (Fig. 2) (W2E, 2014). Adopting communities typically have, on average, lower annual temperatures, higher space heating needs, lower road and population density, and an active forest industry. Despite many similarities, adopting regions vary with respect to other relevant characteristics, including land-ownership patterns, energy prices, market conditions, and a variety of economic and policy factors prevalent at regional and local scales. For example, western states face

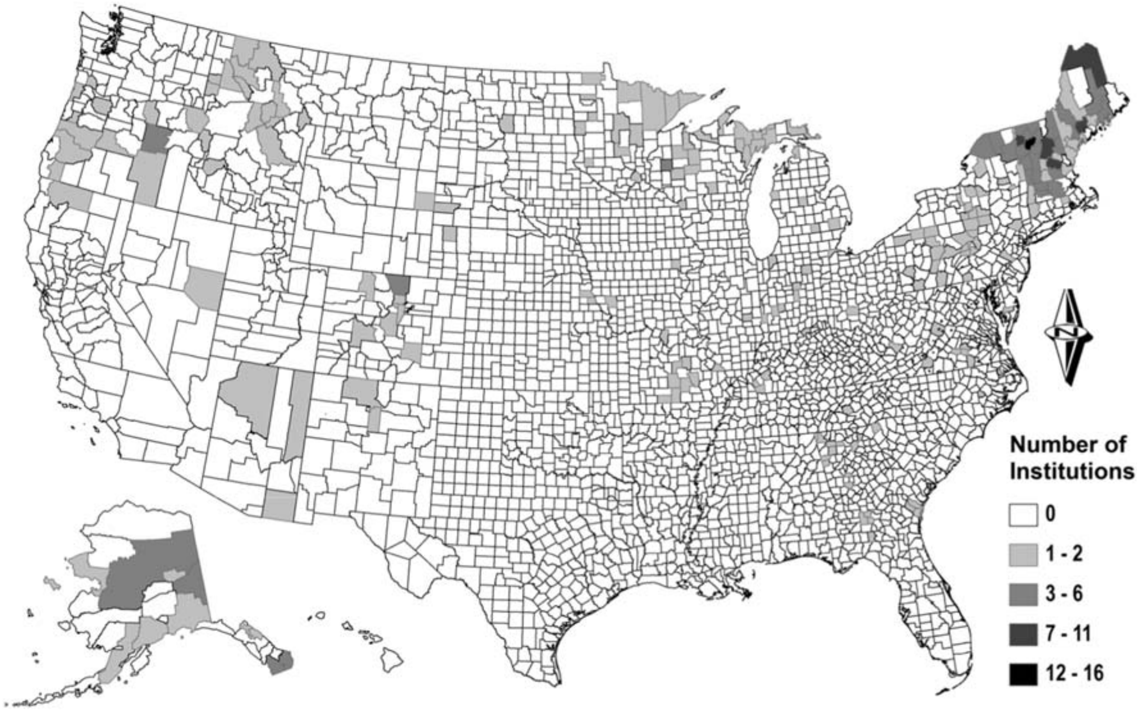

Fig. 1. Map showing counties with institutions currently using woody biomass as a primary heating fuel (W2E, 2014).

the additional limiting factor of difficult geography and terrain, despite widespread forest resources (Skog et al., 2006; U.S. DOE, 2005). Table 1 identifies some commonly cited barriers to local and regional biomass markets, including uncertainty about input collection and processing, and concerns about potential negative environmental or economic consequences for the forest sector. While these types of barriers hinder the establishment and expansion of large scale biofuel or bioenergy facilities, many can be avoided at the institutional scale by optimizing facility size and location (Jenkins and Sutherland, 2014), which is further addressed in Section 3.

2.3. Policy influence on energy and commercial sector use of biomass

The 2007 market value for wood fuel in the U.S. was estimated at $6.5 billion (Summit Ridge Investments, 2007, p. 2) and can be segmented into four sectors: 1) *forest products industry* with 68%

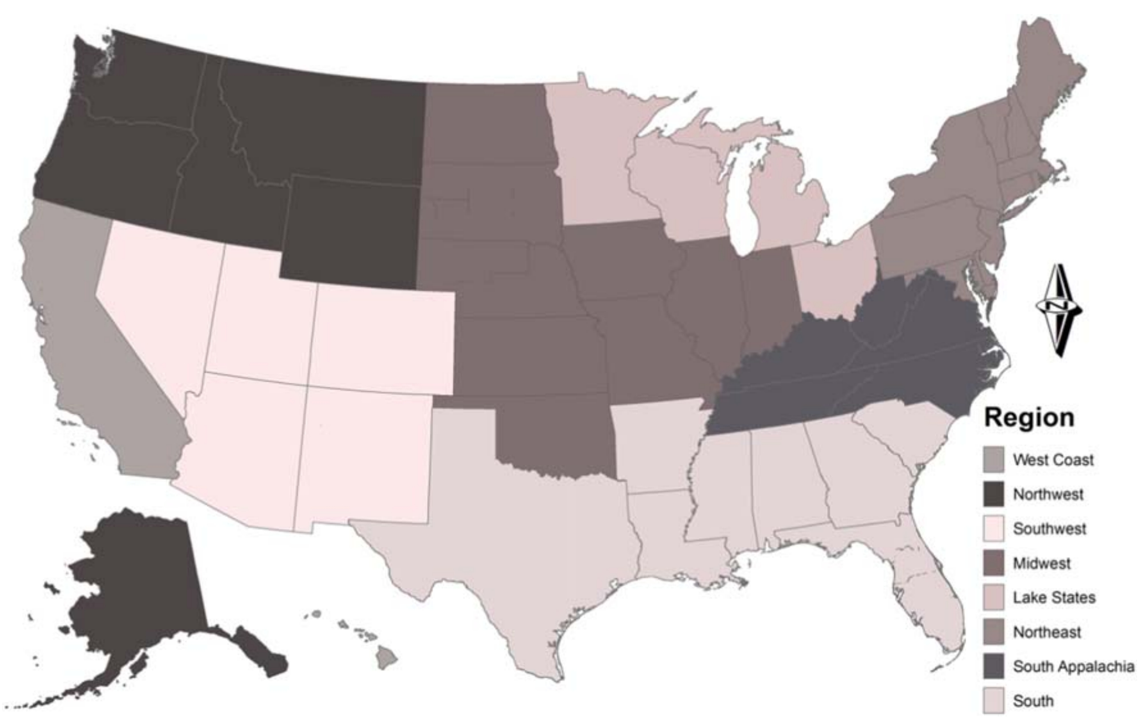

Fig. 2. Map of regions used as indicator variables (Becker et al., 2011).

Table 1
Commonly cited barriers and limiting factors to biomass markets.

Barriers/limiting factors	Source(s)
Major differences in state Renewable Portfolio Standards including funding levels, exemptions for publicly owned utilities, and the presence/lack of buyback programs.	Wiser and Barbose (2008)
Lack of stable, long term supply chains (20 years or longer) both from private and federal lands.	Galik et al. (2009), U.S. GAO (2005)
Lack of transmission line investment, which can limit both in-state and interstate transmission of renewable power.	Wiser and Barbose (2008)
Ecological concerns that too much carbon will be taken off the landscape or that natural lands will be converted to biomass crop lands.	U.S. DOE (2005), Fernando et al. (2011)
Fear of the negative effects that a vibrant woody biomass energy sector might have on other forest resource users, especially wood procurement for pulp and paper operations.	Galik et al. (2009)
Lack of local demand, processing infrastructure and utilization capacity.	Fight et al. (2004), U.S. GAO (2005), Keegan et al. (2006), Nielsen-Pincus et al. (2012)
Concerns that low-valued woody biomass is too dispersed to be efficiently gathered to a central location.	Dykstra et al. (2008), Nielsen–Pincus et al. (2012), Rummer (2008)
High investment costs that are not recaptured until an extended period of time has passed.	Paepe et al. (2006)

of the market share, 2) *residential heating* with 20%, 3) *electric power generation* with 9%, and 4) *commercial heating*, which includes institutional heating, with the remaining 3% (U.S. EIA, 2009, 2010). Large forest industry facilities, including pulp and paper mills, have a long history of using combustion boilers for co-generation of heat and power fueled by waste wood and pulping byproducts like black liquor (Aguilar et al., 2011; U.S. DOE, 2016). Residential sector biomass consumption trends are closely tied to competing energy prices and, to a lesser degree, government policies, showing a lagged positive correlation with competing energy prices (Aguilar et al., 2011; Hardie and Hassan, 1986; Song et al., 2012). For example, after a period of increasing prices from 2001 to 2008, the price of natural gas delivered to residential consumers peaked in 2008 at \$23.61 per 1000 ft^3 (in real 2017 dollars, EIA, 2017). This price is 122% higher than seasonal high price of \$10.63 in 2016 and 178% higher than the seasonal low price of \$8.49 that year (in real 2017 dollars). It is likely that the general upward trend in prices between 2001 and 2008 placed upward pressure on the adoption rate of alternative heating systems, with some time lag, by making alternatives more cost competitive. In contrast, the subsequent lower prices between 2008 and 2017 would remove such pressure, with some lag.

In contrast to these sectors, factors driving biomass consumption in the electric power and commercial sectors cannot be easily separated. Biomass use for power and facility heat is not driven by higher priced fossil-fuels or increased energy costs alone, but is also affected by national and regional government incentives through a variety of policy instruments (Aguilar et al., 2011; Song et al., 2012). Following the oil price hikes of 1973, woody biomass fuel use did not increase until the late 1980s when power plants and commercial firms began to respond to government policies, some of which were authorized a decade earlier (Aguilar et al., 2011).

One of the most notable federal biomass policies is the Public Utility Regulation Policies Act (PURPA) of 1978, which encouraged biomass use in the energy sector by offering a high biomass "avoided cost" purchasing price (Aguilar et al., 2011; Pub. L., 1977). In practice, PURPA required current energy utility providers experiencing a deficit in production to purchase existing renewable energy from other local providers at a cost equal to increasing output with additional fossil-fuel boilers. Other policies that helped stimulate consumption of biomass in the commercial sector include the federal renewable energy tax credit (Pub. L., 1992), the federal business energy investment tax credit (ARRA, 2009), and the Renewable Energy Grant Program (DSIRE, 2014), among others.

Proximity to biomass resources is consistently cited as a strong correlate with adoption of biomass energy systems, and in the U.S. this factor is closely connected with land ownership and management, which vary widely across the country. The U.S. federal government owns around 640 million acres, which accounts for roughly 28% of the 2.27 billion acre land base in the U.S. and is managed by many different agencies with varying missions (CRS, 2012). For example, the Bureau of Land Management (BLM) and U.S. Forest Service (USFS) both have multiple-use, sustained-yield mandates that include timber harvest and potential use of associated woody biomass residues, while the Fish and Wildlife Service (FWS) and National Park Service (NPS) have narrow primary use mandates to conserve plants, animals and unique resources and provide public access, with little to no resource extraction (CRS, 2012). Approximately 93% of federal holdings are in western states consisting of 47% of the land base in the western continental U.S. and 62% of the land base in Alaska (CRS, 2012). However, this includes non-forest land and reserve lands, such as national parks and wilderness areas, neither of which are a significant source of woody biomass from a market perspective. This makes proximity to timberland, which is open to harvesting and meets the minimum level of productivity of 20 cubic feet per acre per year (Helms, 1998), a better metric of potential biomass availability. About 22% of the nation's timberlands are publicly owned, with 78% in private ownership (U.S. Census Bureau, 2012).

Private timberlands and some state lands are a major source of biomass for energy, especially in the Northwest, Northeast and South, with biomass use closely connected to timber production and active forest management. Though timber production on federal land has declined significantly over the past 25 years, federal agencies have implemented a number of policies to encourage the removal and use of woody biomass resources on federal, state and private lands (Becker et al., 2009). Leading the efforts are the USFS and BLM in conjunction with the Department of Energy (DOE). These agencies prescribe silvicultural treatments for timber harvest and forest restoration, carry out forest thinning and biomass removal near communities at risk of wildfire under NFP (Schoennagel et al., 2009), conduct research, provide education and consultation to the public (U.S GAO, 2005), and award grants to businesses, schools, Native American tribes and others for biomass utilization. The authority to conduct such activities is granted by a variety of laws and policies, including the NFP (NFPORS, 2014), the Biomass and Research Development Initiative (Pub. L., 2000), and the Healthy Forest Restoration Act (Pub. L., 2003).

While federal policies and agencies have a major influence on the biomass market in the U.S., state policies better reflect local and regional attitudes towards biomass use, as well as the unique challenges within local biomass markets (Aguilar and Saunders, 2010). Many states have designed and implemented policies aimed at making woody biomass consumption economically competitive. For example, in the 1980s, California aggressively pursued biomass energy production through the Interim Standard Offer 4 (ISO4), which provided guaranteed rates for bioenergy facilities for a limited time (Dykstra et al., 2008). More recently, Michigan passed the Clean, Renewable, and Efficient Energy Act (Public Act 295) in 2008 to strengthen its renewable energy sector (Leefers, 2011). States can also coordinate their policies regionally. For example, in 2005 seven states in the northeastern U.S. joined an agreement to implement the Regional Greenhouse Gas Initiative (RGGI), which is considered the first mandatory market-based program to reduce greenhouse gas emissions in the U.S.

Polices passed by foreign governments also impact U.S. biomass markets. Intending to reduce greenhouse gas emissions, E.U. countries have passed public policies and financial incentives supporting biomass use, which has had a major impact on industrial wood pellet production in the U.S., especially in the South (Qian and McDow, 2013). E.U. countries widely use woody biomass for power production and institutional and district heating applications. For example, Austria and Sweden experienced six and eight fold increases, respectively, in biomass district heating during the first decade of the 21st century largely due to national and local policy incentives (Dong et al., 2009). Ninety percent of wood pellet trade between the U.S. and the E.U. is with the United Kingdom (U.K.), the Netherlands and Belgium, with the fastest growing market in the U.K., which consumed 9.8 million tons of wood pellets in 2010, up from 3.8 million tons in 2005 (Qian and McDow, 2013; Verhoest and Ryckmans, 2012). Increased wood pellet trade between the U.S. and Europe's top three importers is, in part, possible due to adequate port capacity of E.U. trading partners (Verhoest and Ryckmans, 2012), as well as adequate production capacity in the U.S. and Canada and supply chains that are considered environmentally sustainable.

3. Methods and data

3.1. Statistical methods

This study identifies key determinants driving the institutional use of small woody biomass heating systems. A retrospective cross sectional zero-inflated negative binomial (ZINB) model is used to estimate the count of biomass heating systems in all U.S. counties and county equivalents (e.g. boroughs in Alaska and parishes in Louisiana). The county or county equivalent is the largest administrative division of U.S. state government. A ZINB statistical model estimates the count of events, where this study defines an event as an institution using woody biomass heat. Institutions are defined as primary and secondary educational facilities (both private and public), hospitals, government buildings, prisons, military bases, and community gathering facilities, such as community halls, recreation centers, and other public buildings.

Count data theoretically follow a Poisson distribution where the mean equals the variance (Hu et al., 2011). However, in practice this assumption is often violated due to overdispersion where count data show greater variability than predicted by the Poisson distribution (Zuur et al., 2009). Among other things, overdispersion can be driven by unobserved heterogeneity (Phang and Loh, 2014) resulting in an excessive number of zeros and a variance that far exceeds the mean. In the sample, the count of institutional biomass systems has a mean of 0.13 and a variance of 0.46 (standard deviation = 0.68), providing evidence of overdispersion. Should overdispersion occur in nonnegative count data, theory suggests that the Negative Binomial (NB) distribution offers superior fit compared to the Poisson (Hu et al., 2011).

In addition to considering how excessive zero counts affect the mean and variance, the origin of zero counts must also be considered (Hu et al., 2011). In the context of institutions using woody biomass to produce heat, excessive zero counts could be the result of restrictions on biomass extraction due to *the Law of Location for Extraction Industries.*[2] In areas where woody biomass is readily available, additional zero counts could result from market constraints, or institutions lacking the appropriate infrastructure and technology needed to use woody biomass as an energy source (Nielsen-Pincus et al., 2012); a similar constraint to co-firing biomass in coal-fired power plants has been observed (Aguilar et al., 2012).

If zeros in overdispersed count data are believed to come from a single data generating process (DGP) and represent true zero counts, then Zero Altered models (i.e. Hurdle) are appropriate (Hu et al., 2011; Zuur et al., 2009). On the other hand, if zero counts are believed to come from two DGPs; with excess zeros due to structural barriers (e.g. *Law of Location for Extraction Industries*) and true zero counts due to sampling chance, then Zero Inflated (ZI) models where structural zeros are modeled independently from sample zeros are more appropriate (Hu et al., 2011; Phang and Loh, 2014). Ignoring zero inflation can result in biased standard errors (Zuur et al., 2009), and in situations where zero inflation is evident there is a high chance of overdispersion. The presence of overdispersion makes the ZINB distribution an attractive alternative to the Zero Inflated Poisson (ZIP) (Hu et al., 2011).

In this study, structural zeros and sample zeros are modeled independently using a ZINB mixed model, as supported by theory and the observed distribution of the dependent variable. Structural zeros result from counties with structural constraints such as a lack of heating needs (i.e. warm temperatures) or lack of biomass resources, and follow a ZI distribution (logistic model). Sample zeros that originate from counties that are otherwise suitable for woody biomass heating but have not adopted biomass technologies follow a NB distribution (count model).

In the ZINB model the count of institutions using woody biomass is Y_i, where $i = 1, \ldots, n$ has a probability mass function given by:

$$\Pr(Y_i = y_i) = \begin{cases} p_i + (1-p_i)\left(\dfrac{\phi}{\mu_i+\phi}\right)^{\phi}, & \text{if } y_i = 0 \\ (1-p_i)\dfrac{\Gamma(\phi+y_i)}{\Gamma(y_i+1)\Gamma(\phi)}\left(\dfrac{\mu_i}{\mu_i+\phi}\right)^{y_i}\left(\dfrac{\phi}{\mu_i+\phi}\right)^{\phi}, & \text{if } y_i = 1,\ldots,k \end{cases}$$

where $\Pr(Y_i = y_i)$ is the probability of county i containing y institutions using woody biomass, $0 \le p_i \le 1$, $\mu_i \ge 0$, ϕ^{-1} is the dispersion parameter with $\phi > 0$, and $\Gamma(\cdot)$ is the gamma function (Garay et al., 2011). The mean and the variance are $E(Y_i) = (1 - p_i)\mu_i$, and $Var(Y_i) = (1 - p_i)\mu_i(1 + \mu_i\phi^{-1} + p_i\mu_i)$. When $p_i = 0$, the dependent variable Y_i has a NB distribution parameters with the mean μ_i and dispersion parameter φ (i.e. $Y_i \sim NB(\mu_i, \varphi)$) (Garay et al., 2011).

In application the parameters μ_i and p_i depend on vectors of explanatory variables z_i andx_i, respectively, resulting in the following models (Garay et al., 2011):

$$\log\left(\frac{p_i}{1-p_i}\right) = z_i^T\gamma \quad \text{and} \quad \log(\mu_i) = x_i^T\beta, \quad i = 1, \ldots, n,$$

where $\gamma = (\gamma_1, \ldots, \gamma_q)^T$ and $\beta = (\beta_1, \ldots, \beta_s)^T$ are unknown parameters for the ZI and NB models, respectively (Garay et al., 2011).

3.2. Data

The scope of the study is the U.S., represented by 3142 counties or county equivalents and the observation period is calendar year 2014. Datasets used in the analysis have nationwide coverage at county, state or regional resolution, with the exception of Washington D.C., which is thus excluded from the analysis. Counties were chosen as observational units because these are the smallest geographic units with full Census and Energy Information Administration data coverage for the study area. In addition, forest residue production is reported at the national level on a county basis, but not at sub-county resolution, to preserve confidentiality in industry surveys. The response variable Y_i (count of institutions using biomass in heating systems) was obtained from the Wood2Energy database sponsored by the Endowment for Forestry and Communities Incorporated, Biomass Thermal Energy Council, Biomass Power Association, and the Pellet Fuels Institute (W2E, 2014). Of the 3142 counties there are 225 non-zero observations and a total of 401 institutions using biomass fuels in operational heating systems in 2014 (Fig. 1). The states of Alaska and Hawaii are not contiguous with the other 48 states of the continental U.S. and therefore counties in those states are geographic outliers; however, model results are robust to the exclusion of these outlier counties. The institutions

[2] "The extractive industries are, and must continue to be located by the occurrence of their raw materials" (Renner, 1947, p. 169).

Table 2
Independent variables used to estimate the ZINB model parameters.

Variable	Description/(resolution)	Units	Source
Y – dependent variable			
Institutions	Institutions currently using biomass heating systems	Institution (Count)	Wood2Energy (2014)
Physical restrictions			
Heating degree days	1981 to 2010—Total average heating degree days (county)	Days (1000)	National Oceanic and Atmospheric Administration (2014)
Population density	2010—Population per 1000 m^2 (county)	People per 1×10^6 m^2	U.S. Census Bureau (2013)
Forest residue	2007—Logging residues and other removals (county)	Cubic meter (1×10^7)	USDA, USFS Timber Product Output (2007)
Population	2010—Population (county)	People (1×10^5)	U.S. Census Bureau (2013)
County area	2010—County area	Square meter (1×10^9)	U.S. Census Bureau (2013)
Economic restrictions			
Natural gas prices	2008 to 2010—Commercial natural gas three year average price (state)	Nominal U.S. Dollars ($) per 1000 ft^3	U.S. Energy Information Administration (2013)
House value	2008 to 2012—Median value of owner-occupied housing (county)	Nominal U.S. dollars ($) (1000)	U.S. Census Bureau (2013)
Road density	2013—Primary (interstates) and secondary road (main state and county highways) (county)	Meters of road per 1000 m^2	U.S. Census Bureau (2013)
Port capacity	2008 to 2012, Average port capacity of principal ports. (county)	Short tons (1×10^5) (metric tons (9.07×10^4))	U.S. Army Corps, Navigation Data Center, Waterborne Commerce Statistics Center (2014)
Policy variables			
Biomass planned	2006–2010—Biomass removal planned in National Fire Plan (NFP) (county)	Square kilometer	National Fire Plan Operating and Reporting System (2006–2010)
Federal land	2005, 2012—Proportion of land managed by Federal Agencies[a] (county)	Proportion	ESRI, National Atlas of the U.S. and the U.S. Geological Survey (2005, 2012)
Total policies	2011—Total number of state policies that effect forest biomass use directly or indirectly. Federal policies are not included. (state)	Policies (Count)	Becker et al. (2011)

[a] Land section 640 acres or larger are included. Private in-holdings <640 acres may be accounted for in federal holdings.

include 176 elementary or high schools (44%), 52 universities or colleges (13%), 52 administrative or government facilities (13%), 37 community facilities (9%), 33 hospitals or medical facilities (8%), 22 correctional facilities (5%), 21 facilities categorized as other (5%), 4 public housing complexes (1%), and 4 military bases (1%) (W2E, 2014).

The selection of explanatory variables is based on three principles of location restrictions (Rawstron, 1958; Renner, 1947): 1) physical restrictions, 2) economic restrictions, and 3) technical restrictions. Physical restrictions limit industry locations to areas with physically derived demand for outputs and where input resources are available, depending highly on the resource pattern of occurrence and density (Rawstron, 1958; Renner, 1947). In the case of biomass heating, physical restrictions constrain location to areas in need of institutional heating that are close to biomass available for harvest, such as actively managed timberlands. Economic restrictions include cost structures of industry (labor, material, land, marketing, and capital) and spatial margins, in particular those of transportation costs (Rawstron, 1958). In this case, as transportation distance from biomass inputs increases, transportation costs may become too large for a biomass boiler to be economically viable due to the low energy density and low thermal conversion factor of biomass fuels compared to fossil-fuels (BEC, 2014; Rummer et al., 2005). Technical restrictions include both the method of production (e.g. biomass combustion boiler) and the organization of administration (e.g. biomass supply chain and boiler operators). In this case, technological advances in biomass heating are prominent when compared to the long average lifespan of an institutional heating system, and installation represents a large capital investment. For these reasons increased scrutiny should be applied to potential adoption locations in light of the first two restrictive principles before a system is installed.

As suggested by the principles of industry location and current literature, selected variables capture physical and economic restrictions on institutional biomass adoption. Technical restrictions are not included as these are either the same for all institutions (e.g. available technologies) or unobservable at the county level (e.g. institutional organization). The role of state and national policies that influence biomass use are considered in addition to location-specific restrictions. Explanatory variables withstanding scrutiny and satisfying data-quality requirements can be found in Table 2, along with a description, units, and sources. Units for all variables were kept in their original format as presented in primary data sources and publications to facilitate replication and use of resultant statistical models.

3.2.1. Data: physical restrictions

The ZI models have three physical restrictions with theoretical grounds to be associated with structural zero counts. The first *Heating Degree Days* (measured in thousands of heating degree days) is a proxy for local heating requirements and is calculated using a base of 65 degrees Fahrenheit (NOAA, 2014). For every degree below 65 degrees on any given day the county receives a heating degree day equal to the difference between 65 degrees and the mean temperature, which resulted in an average of about 5000 heating degree days across all counties (Appendix A). The second variable, *Population Density* measured as people per square kilometer, was included to control for institutional needs of the county. The third and final variable in the ZI model, *Forest Residues*, includes both logging residues[3] and other removable forest management byproducts[4] measured in tens of millions of cubic meters (Milbrandt, 2005). Production of forest residues is directly connected to active forest management and was included as a proxy for woody biomass supply. Inclusion in the ZI model is closely tied to restrictions of industry location – though woody biomass can be transported great distances under certain circumstances, it is generally considered bulky, low in value and inefficient to transport >100 miles, making areas with low or zero forest residues likely to be associated with structural zeros. Data quantifying woody biomass supply more precisely at the sub-county level is unavailable due to its proprietary nature, and there are no datasets that provide full national coverage of biomass prices and market transactions at fine resolution. An increase in each of the variables in the ZI model step is expected to increase the odds of institutions using woody biomass as a fuel source.

[3] "Unused portions of trees cut, or killed by logging, and left in the woods" (Milbrandt 2005, p. 18).

[4] "Trees cut or otherwise killed by cultural operations (e.g. pre-commercial thinning, weeding, etc.) or land clearings and forest uses that are not directly associated with round wood product harvests" (Milbrandt 2005, p. 18).

The NB model also included *Heating Degree Days* and *Forest Residues* because both variables not only affect the odds of a county having at least one institution using a biomass heating system, but also the number of institutions using a biomass heating system. These variables are believed to be associated with both DGPs, which are: 1) excess zeros due to structural barriers (i.e. lack of heating needs or woody biomass supply), and 2) the true count of institutions within a county (i.e. level of heating needs or quantity of woody biomass supply). Though *Forest Residues* are transportable, for modeling purposes it is assumed these are utilized within individual counties due to high transportation costs (Nielsen-Pincus et al., 2012). Because *Forest Residues* are highly correlated across adjacent counties, also including *Adjacent Forest Residues* would likely cause severe multicollinearity (Spearman's correlation between *Forest Residues* and total *Adjacent Forest Residues*, rho = 0.87, p-value ≤ 0.0001).

In addition to *Heating Degree Days* and *Forest Residues*, other physical restrictions included in the NB model included total *Population* and *County Area*. Total *Population* was included as a proxy for the total number of institutions in a county. As the population rises, so does the number of institutions. Theoretically, an increase in the number of institutions in a county increases the expected number of institutions using biomass, ceteris paribus. Similarly, *County Area* measured in billions of square meters was included to control for the quantity of land in the county's administrative domain. As a county increases in area it is expected to contain more institutions, and thus more institutions using biomass.

3.2.2. Data: economic restrictions

In addition to physical restrictions, economic restrictions were included in the NB models. Commercial *Natural Gas* Price was included to represent competing energy prices. Where fossil-based energy prices are high, the count of institutions that turn to biomass as an alternative heating fuel is also expected to be high. Prices of other fossil fuels used for heating were not available for the full study area, but track closely with natural gas price. As noted in Table 2, natural gas price was calculated as the three year average price from 2008 to 2010 for commercial natural gas at state resolution. This period includes a price spike in summer of 2008. Adjusted for inflation, peak 2016 price was less than half the peak 2008 price thanks in large part to the production boom attributable to hydraulic fracturing technology.

Owner-occupied median *House Value* serves as a proxy for county affluence levels. As the affluence level increases, so does the demand for a cleaner environment and renewable energy (Selden and Song, 1994), which in turn may increase the expected number of institutions using a woody biomass heating system. More affluent communities are also more likely to have the financial resources to install a new biomass heating system. However, it is important to note that affluent communities may not view biomass combustion as an attractive renewable energy. For example, a recent study by Yoo and Ready (2014) carried out a choice experiment in Pennsylvania and found that among other renewable energy options, biomass combustion was viewed as unfavorable. This may be tied to impact on local air quality, especially particulates (Obaidullah et al., 2012).

The variable *Road Density*, which includes both primary and secondary highways but excludes smaller roads such as city streets, was included as a proxy for transportation costs and access to biomass stocks, specifically transportation logistics that facilitate the flow of raw materials from the forest to a facility. As road density increases so does the access to woody biomass resources, as well as the infrastructure available to transport biomass to a central location. However, high road densities are associated with urbanization and residential natural gas infrastructure, and potentially a reduction in active forest management and woody biomass available for energy production. To control for urbanization the model includes *Population* and *County Area* that together control for population density of each county. If urbanization is not fully captured with *Population* conditioned on *County Area*, then some of the remaining urbanization effect could be captured by *Road Density*, with high road densities associated with urbanization. In that case, the coefficient on *Road Density* represents the net effect of access to biomass and the remaining urbanization effect on adoption of biomass heating systems.

The *Port Capacity* of 150 principal ports measured in hundred thousand short tons (1 short ton equals 0.907 metric tons) was included as a proxy for waterborne commerce in the U.S., and was calculated as the average capacity from 2008 to 2012, for the years the port was considered a principal port. This resulted in 164 principal ports attributed to 156 counties.[5] While domestic institutional customers do not directly use ports for transportation of biomass, proximity to principal ports may increase the level of wood pellets and chips being exported to the E.U. and elsewhere (Dong et al., 2009; Qian and McDow, 2013), reducing local supply all else equal. Alternatively, by facilitating low-cost transportation of biomass and efficient bioenergy supply chains, the presence of port capacity may have a positive, indirect effect on institutional use of woody biomass near principal ports. A priori effects of principal port capacity are ambiguous, but this variable was included primarily because of the huge increase in wood pellet and energy chip exports from the U.S. from 2009 to 2014.

3.2.3. Data: policy variables

In addition to physical and economic restrictions, policy variables were included in the NB model to capture how federal and state policies affect adoption. *Biomass Planned* serves as a proxy for federal and state land management policies that are likely to produce available biomass from reducing fuel loads in accordance with NFP. Fuel reduction on forestland near populated areas has been identified as a critical potential source of biomass for energy because it generally occurs near road infrastructure, which facilitates logistics, and because biomass removals are a relatively small marginal cost associated with larger investments in risk mitigation, potentially reducing the cost of production when compared to a standalone commercial enterprise. This variable includes treated lands owned by Federal and State governments, as well as adjacent private lands and lands owned by private individuals and corporations.

The proportion of *Federal Land* in each county is also included to represent large portions of land ownership managed under federal law and policy. In general, federal land in the U.S. is managed quite differently from private land, with different constraints on extractive and commercial activities. Proportions of federal land were calculated using Environmental Systems Research Institute's ArcGIS software (ESRI GIS; ESRI, 2012). Higher values of both *Biomass Planned* and *Federal Land* are expected to be associated with a higher count of institutions in a county using a biomass heating system.

As noted in Section 2.3, within the federal land category, there is significant variability in the goals, objectives and activities of different land-holding agencies. To capture the potential effect of ownership by different agencies on biomass policy, *Federal Land* is further partitioned by agency in model extensions, with primary federal landowners designated as USFS, FWS, NPS, BLM, Bureau of Indian Affairs (BIA), Bureau of Reclamation (BOR), and Department of Defense (DOD).

To better understand the effects of state policies, *Total Policies* in each U.S. state supporting the supply chain of woody biomass use was obtained from a prior publication by Becker et al. (2011). The purpose of this variable was to evaluate the effect of policies favorable to biomass energy, but policies in Becker et al. (2011) were not excluded from the analysis for containing onerous qualities that may deter biomass use, such as regulations on fine particulate matter or requirements for minimum efficiency of energy conversion. A higher number of policies

[5] "Principal ports" are the top 150 importers/exporters in terms or short tons shipped, which varies from year to year. Fourteen ports entered/exited the top 150 "principal ports" from 2008 to 2012.

Table 3
Policy instruments that encourage the use of forest based woody biomass.

Policy type	Policy examples
Cost share and grants	Cost-share, grants and rebates
Technical assistance	Training programs, technical assistance
Financing	Bonds, loans and other financial support
Procurement	Procurement mandates and net metering
Rules and regulations	Renewable energy standards, electricity grid interconnection standards, green power programs, public benefit funds, equipment certifications, and biomass harvest guidelines
Tax incentives	Sales tax credits, corporate and production tax credits, personal tax credits, and property tax credits

Source: Becker et al. (2011).

supporting the use of biomass are expected to be associated with a higher count of institutions using biomass.

State policies are also ideally suited to alleviate biomass market barriers related to high start-up costs and long payback periods, and an associated lack of cost share programs, grants and financing (Paepe et al., 2006; Thornley and Cooper, 2008), but this hypothesis has not been adequately tested for small-scale biomass heating systems. To explore these relationships and other aspects of the biomass supply chain, a model extension delineates *Total Policies* into the policy types in Table 3.

Of the included variables, *Total Policies* is the most likely to exhibit characteristics of endogeneity, violating the assumption of exogenous predictors. Endogeneity could materialize from two sources giving a false signal of association: 1) biomass policies that were passed to support existing biomass plants; or 2) woody biomass policies that are only passed in states with woody biomass resources (Hitaj, 2013). The first is unlikely because small heating systems are relatively rare in U.S. institutions and are not usually the focus of policy because of their low consumption of woody biomass, and generally small impact on the energy sector when compared to large biomass facilities (e.g. power plants). The second source of endogeneity is not a concern due to the wide breadth of policies used, which target renewable energy in general rather than being focused directly on woody biomass. Furthermore, as a signal of endogeneity, one would expect moderate to high correlation between the number of policies and the number of institutions using a woody biomass heating system, but this is not observed in the dataset, with correlation of $r = 0.03$ for *Total Policies* and a maximum of $r = 0.11$ for the *Cost Share/Grant* type policies.

3.2.4. Data: geographic variables

Regional indicator variables from Becker et al. (2011) (Fig. 2), and the latitude and longitude of the geographic center of each county are also included to control for geographic location. Becker et al. (2011) compared policies by region of the country to identify geopolitical and physical resource patterns, and observed both commonalties and variation among these regions. Including regional indicator variables controls for regional heterogeneity within the model. Descriptive statistics for the dependent and independent variables can be found in Appendix A.

3.3. Model diagnostics

Before interpreting the empirical results, we tested the ZINB model specification for overdispersed and zero inflated count data against the un-nested NB model (overdispersed), and the nested Poisson (neither overdispersed nor zero inflated) and ZIP models (zero inflated). The following model diagnostics and comparisons were carried out using Stata 12.1 (StataCorp, 2011): 1) a *t*-test on the dispersion parameter alpha[6] (α) to determine if there is overdispersion in the response indicating the NB distribution is preferred to the Poisson (Table 4); 2) a Vuong test of un-nested ZINB and NB models to determine if overdispersion in the response is the result of zero inflation (Table 5, columns 1 and 2); and 3) a likelihood ratio test of the ZINB model and nested ZIP model to confirm that the ZINB model does a better job modeling zero inflation than the ZIP model (Table 5, columns 3 and 4). Test results showed a preference for NB over Poisson, ZINB over NB, and ZINB over ZIP for each of the three models, with each being statistically significant at the 1% level. In addition, the percent of counties correctly estimated was 91.41% (2872 counties), 91.53% (2876 counties), and 91.82% (2885 counties) for Models 1, 2, and 3, respectively (Table 4), and the count distribution of the true and modeled populations are similar across all models.[7]

4. Results

The base model (Model 1) estimates the number of institutions using biomass heating systems within a county's borders using the fewest number of variables of the three models. Federal land management was delineated by agency in Model 2 to assess effects of agency type under the rationale that different agency mandates potentially affect biomass policy and production. Model 3 delineates state biomass energy policies by type to evaluate which policy instruments are associated with the number of institutions using a woody biomass heating system.

4.1. Model 1

Some general conclusions and model interpretations can be drawn from Model 1 (Table 4). When predicting the odds of structural zeros in the ZI model step, all slope coefficients are negative and statistically significant. More heating degree days, higher population density, and more forest residues decrease the odds of a county being a structural zero. Referring to the NB portion of the model, variables that increase the likely count of institutions using woody biomass include *Heating Degree Days*, commercial *Natural Gas Prices*, median *House Value*, available *Biomass Planned* from lands treated under the NFP, and the proportion of *Federal Lands* in the county. Conversely, an increase in *Road Density* and *Port Capacity* decreases the likely number of institutions using woody biomass.

4.1.1. Model 1 results: physical restrictions

Heating Degree Days appears in both model steps, and is a good variable to illustrate the interpretation of model parameters. Like other binary models, the ZI model gives coefficients (γ) that are in terms of log odds,[8] and are easiest and most accurately interpreted when transformed to odds ratios (ORs). ORs are calculated by taking the exponential of the coefficients. Negative coefficients result in ORs less than one. Heating degree days has an OR of 0.813, which indicates that the addition of 1000 heating degree days is associated with a 0.813 factor decrease in the odds of a structural zero, i.e. that the county does not contain an institution using biomass. An alternative is to define success as having an institution that uses woody biomass. This would result in inverse odds ratio to those displayed in the ZI step of the models in Table 4. For example, an addition of 1000 heating degree days is associated with a 1.23 (=1/0.813) factor increase in the odds that the county contains an institution using woody biomass, and the addition of 2000 heating degree days (just less than one standard

[6] Some authors use lowercase alpha (α) for the overdispersion parameter, while others use lowercase phi (φ).

[7] Population (mean, std. dev., skewness, kurtosis) True (0.1276, 0.6756, 11.1827, 183.0727), Model 1 (0.1321, 0.4684, 10.2248, 150.2691), Model 2 (0.1296, 0.4476, 8.8462, 100.5661) Model 3 (0.1283, 0.4463, 8.7312, 96.1523).

[8] $\beta = \log(\text{odds of success} / \text{odds of failure}) = \log((p_{success} / (1\text{-}p_{success})) / (p_{failure} / (1\text{-}p_{failure})))$, where $p_{success}$ is the probability of a structural 0, and $p_{failure}$ is the probability of not being a structural zero (IDRE, 2014a).

Table 4
Results for the Zero Inflated Negative Binomial (ZINB) Model 1, Model 2, and Model 3 estimating the number of institutions using decentralized woody biomass heating systems.

	Model 1			Model 2			Model 3		
Independent variables	Coeff.	[OR] (IRR)	Robust SE	Coeff.	[OR] (IRR)	Robust SE	Coeff.	[OR] (IRR)	Robust SE
Zero Inflated (ZI-Logistic)									
Physical restrictions									
Heating degree days	-0.207^{**}	[0.813]	0.105	−0.271	[0.763]	0.228	−0.255	[0.775]	0.190
Population density	-0.044^{*}	[0.957]	0.025	−0.044	[0.957]	0.027	-0.043^{*}	[0.957]	0.026
Forest residues	-2.021^{***}	[0.133]	0.597	-2.086^{**}	[0.124]	0.911	-2.009^{***}	[0.134]	0.751
Negative binomial (NB-Count)									
Physical restrictions									
Heating degree days	0.190^{*}	(1.210)	0.099	0.178	(1.194)	0.109	0.138	(1.148)	0.104
Forest residues	0.003	(1.003)	0.007	0.001	(1.001)	0.007	0.002	(1.002)	0.007
Population	−0.001	(0.999)	0.030	0.004	(1.004)	0.030	0.017	(1.017)	0.029
County area	−0.001	(0.999)	0.002	0.004	(1.004)	0.003	0.004	(1.004)	0.003
Economic restrictions									
Natural gas prices	0.265^{***}	(1.304)	0.056	0.298^{****}	(1.347)	0.063	0.256^{***}	(1.291)	0.063
House value	0.004^{***}	(1.004)	0.001	0.003^{**}	(1.003)	0.001	0.002^{*}	(1.002)	0.001
Road density	-1.079^{*}	(0.340)	0.629	−1.036	(0.355)	0.638	−1.081	(0.339)	0.659
Port capacity	-0.016^{**}	(0.984)	0.008	−0.012	(0.988)	0.008	−0.012	(0.988)	0.008
Policy variables									
Biomass planned	0.009^{**}	(1.009)	0.004	0.012^{**}	(1.012)	0.005	0.012^{**}	(1.012)	0.005
Prop. federal land	0.822^{***}	(2.275)	0.300						
Proportion USFS				1.139^{***}	(3.122)	0.304	1.082^{***}	(2.951)	0.303
Proportion FWS				-4.241^{*}	(0.014)	2.434	-4.606^{*}	(0.010)	2.671
Proportion NPS				−2.357	(0.095)	1.613	−2.180	(0.113)	1.572
Proportion BLM				−0.860	(0.423)	1.127	−0.719	(0.487)	1.194
Proportion BIA				−0.698	(0.498)	1.119	−0.361	(0.697)	0.936
Proportion BOR				−11.895	(0.000)	30.453	−8.094	(0.000)	28.619
Proportion DOD				1.661	(5.267)	2.920	1.690	(5.420)	2.846
Total policies	−0.028	(0.972)	0.023	−0.030	(0.970)	0.024			
Cost share & grants							−0.103	(0.902)	0.095
Technical assistance							−0.007	(0.993)	0.067
Financing							0.181	(1.199)	0.120
Procurement							-0.313^{**}	(0.731)	0.124
Rules & regulations							0.047	(1.048)	0.084
Tax incentives							−0.044	(0.957)	0.039
Alpha	0.640^{***}		0.199	0.654^{***}		0.246	0.548^{***}		0.203
Log pseudo-likelihood			−793.93			−787.68			−781.86
Wald test	$H_0: \gamma = 0, \beta = 0$ $\chi^2 = 447.27^{***}$			$H_0: \gamma = 0, \beta = 0$ $\chi^2 = 454.46^{***}$			$H_0: \gamma = 0, \beta = 0$ $\chi^2 = 560.35^{***}$		
Likelihood ratio test				H_0 : Model 1 $\chi^2 = 12.50^{*}$			H_0 : Model 2 $\chi^2 = 11.65^{**}$		
Correctly estimated (residual ± 0.499)			2872			2876			2885

All models include controls for latitude and longitude, and regional fixed effects. $N = 3142$; Non-zero $N = 255$.
* $p < 0.1$.
** $p < 0.05$.
*** $p < 0.01$.

deviation) increases these odds by a factor of 1.51 (=1/(0.813^2)),[9] ceteris paribus at mean values. Similar interpretations can be drawn for *Population Density* and *Forest Residues*.

The NB count model gives coefficients (β) that are in terms of the log difference between expected counts (μ),[10] and are most accurately interpreted as incidence rate ratios (IRR). Transformation of the parameters to IRRs is accomplished by taking the exponential of the coefficients. For *Heating Degree Days* in Model 1, an IRR of 1.21 indicates that an addition of 1000 heating degree days is associated with a 1.21 factor increase in the likely count of institutions using biomass as a heating fuel. For the average county, an increase of 2000 heating degree days is associated with a 1.46 (=1.210^2) factor increase in the likely count of institutions using biomass.

While the availability of forest residues is an important aspect in the ZI model step, this does not hold for the NB model, which is conditioned on the odds of structural zeros. Though available forest residues are essential for institutions installing woody biomass heating systems, counties producing forest residues do so at large enough quantities needed to run many heating systems, resulting in a weak signal of the count of adopting institutions.

4.1.2. Model 1 results: economic restrictions

There is strong evidence that some economic restrictions are associated with the number of biomass heating facilities. Higher commercial *Natural Gas Prices* and owner-occupied median *House Value* increase the number of expected institutions using biomass. Counties that experience future increases in energy prices or economic growth may also see increases in the adoption of biomass heating systems.

Conversely, higher *Road Density* is not significant in the preferred model specification, and there is economic evidence that the addition

Table 5
Tests of ZINB model fit.

	Vuong test[a] ZINB vs. NB		Likelihood ratio test[b] ZINB vs. ZIP	
	(1) Statistic (V[c])	(2) p-Value	(3) Statistic(z-score)	(4) p-Value
Model 1	4.45	<0.0001	46.37	<0.0001
Model 2	3.89	0.0001	74.12	<0.0001
Model 3	3.90	<0.0001	65.53	<0.0001

[a] H_0: NB is preferred to ZINB.
[b] H_0: ZIP is preferred to ZINB.
[c] V is the Vuong statistic as described in Vuong (1989).

[9] A multiunit change interpretation of the OR = OR^ΔX, where OR = Exp(β), β is the coefficient of variable X, and ΔX represents a multiunit change (Hilbe, 2008). Applies to IRRs as well.

[10] $\beta = \log(\mu_{x+1}) - \log(\mu_x)$, where x represents the dependent variable and x + 1 represents a one unit increase in x (IDRE, 2014b).

of one standard deviation of *Port Capacity* changes the expected number of institutions using a woody biomass heating system by a factor of 0.86 (=0.984^9.3). These may be the result of urbanized counties being characterized by high road and port density. Urban areas with dense road networks and industrial infrastructure more commonly have centralized fuel distribution systems to efficiently meet heating needs by providing heating fuels in the form of natural gas, propane, or fuel oil, as well as electricity delivered by the utility grid. These areas also tend to be more distant from actively managed forests and have less cultural connection to wood heating using traditional methods, such as wood stoves and fireplaces, which are more common in rural areas and may be banned in urban areas with a history of poor air quality.

4.1.3. Model 1 results: policy variables

Of the included policy variables, higher *Biomass Planned* values and proportions of *Federal Land* increase the expected number of institutions using biomass. Counties with higher levels of NFP fuel treatment activities are likely to experience further adoption, and the addition of one standard deviation in the area of *Federal Land* as a proportion of the county land base (0.24) is associated with just under a 1.22 (=2.275^0.24) factor increase in the expected count of institutions using biomass. The latter effect, while holding economic and statistical significance, has narrow implications for state and local policy, in part due to the fixed nature of federal land ownership and the relatively negligible control local governments have in influencing management of federal lands. However, the significance of federal lands does suggest that the management of these lands through the implementation of federal policy is an important variable when considering the adoption of woody biomass heating systems.

4.2. Model 2 – model extension

4.2.1. Model 2 results: federal policy variables

To further investigate the impact that federal land holdings have when estimating the number of institutions using woody biomass heating systems, Model 1 was expanded to disaggregate federal land ownership by agency (Table 4, Model 2). The *Proportion of USFS* lands has a statistically significant positive association with the expected count of institutions. Conversely, the *Proportion of FWS* and *NPS* lands have negative associations with the expected count of adopting institutions, with statistically significant and suggestive influence (p-value = 0.14), respectively. The negative associations of FWS and NPS lands are not surprising given that their mandates and management do not include resource extraction.

Likewise, the parameter sign of the two largest land holding agencies (BLM and USFS) matched expectations for a few reasons. First, much of the land administered by the USFS is forested and generates woody biomass through active management designed to meet a wide range of management objectives. Conversely, BLM land holdings are dominated by woodlands (e.g. pinyon-juniper woodland) and rangeland, much of which is used for grazing or fossil-fuel and mineral resource extraction. The type of available biomass is important to note because the Wood2Energy database focuses on the use of tree-derived woody biomass, which is more common on USFS land. Also, communities close to USFS offices and operations have access to USFS personnel and resources, which may impact both biomass supply and technology adoption. Second, while both agencies work closely with the Department of Energy in implementing federal policy instruments that encourage the use of woody biomass through the facilitation of biomass grants and educational opportunities, the USFS lands certainly produce more woody biomass than other agency holdings. Results show that the presence of USFS land has significant positive impact on the number of institutions using woody biomass, while the effect of BLM land appears to be less impactful and more ambiguous in nature.

4.3. Model 3 – model extension

4.3.1. Model 3 results: state policy variables

A priori, state *Total Policies* were expected to encourage institutional use of biomass heating. To further explore policy effects *Total Policies* were delineated by type as described in Table 3 based on prior work by Becker et al. (2011). Model 3 tests the assertion that biomass consumption in the commercial sector, which includes institutions, is not driven by higher priced alternative fuels or increased energy costs alone, but is also affected by regional government incentives through a variety of policy instruments (Aguilar et al., 2011; Song et al., 2012).

Across the nation as a whole, *Financing* policies encourage institutional use of woody biomass the most (p-value = 0.14), giving suggestive but inconclusive evidence in support of the hypothesis that large financial startup costs are a major barrier to new, small biomass facilities (Table 4, Model 3). On the other hand *Procurement* policies appear to have a significant negative effect. It is worth emphasizing that *Procurement* policies are not focused on biomass procurement or technology acquisition, but rather on energy procurement such as net metering on utility grids or bio-based products and liquid fuels procurement, and therefore are not directly aimed at woody biomass use. For example, net metering requires local utilities to buy back excess electricity produced by biomass facilities, but most small woody biomass facilities only produce heat for space heating needs. Alternatively, there may be unobserved heterogeneity in the *Procurement* policy variable that is not explained within the model.

Other policy coefficients were largely insignificant. As supported by Becker et al. (2011), biomass policies in general may not efficiently or effectively be targeting small biomass heating systems, but rather are focusing primarily on the manufacturing and utility sectors. Another possible explanation is that the small degree of cross sectional variation in state-level policy types may be limiting the statistical associations that can be quantified (Hitaj, 2013).

4.4. Model comparison and expansion map

Likelihood ratio tests were carried out for model comparison between Model 2 and the nested Model 1 and between Model 3 and the nested Model 2 (Table 4). Based on this information, it was determined that Model 3 was preferred to make in-sample forecasts for expected industry expansion (Fig. 3, Appendix B).

Cutoff thresholds were defined in a two stage process—counties with residuals less than −0.5 are defined as “likely adopters”, and counties with residuals less than −1.0 are defined as “most likely adopters”. Likely adopters include counties in the *Northwest* and *Northeast*, as well as in Michigan in the *Lakes States* region, and Colorado and New Mexico of the *Southwest* region. Most likely adopters include counties in the *Northwest* and *Northeast* (Fig. 3). Refer to Appendix B for a complete list.

Forecasted adopters (46 likely and 15 most likely) on average have higher heating needs (7639 *Heating Degree Days*), a lower *Population Density* (0.92 people/1×10^6 m^2), and more *Forest Residue* produced within the county (3.77×10^7 m^3). These counties also experience higher than average *Natural Gas Prices* ($11.56/1000 ft^3) and median *House Values* ($225,600), in addition to a higher *Proportion of USFS* lands (0.18) and more lands that went through fuel reducing treatments (12.23×10^6 m^2) under the *NFP*.

On average, forecasted adopters in the *Northwest* (11 likely and 3 most likely) are very rural (0.08 people/1×10^6 m^2), have high heating needs (7639 *Heating Degree Days*), and coexist with a vibrant wood products industry (5.15×10^7 m^3 of *Forest Residue*) and a high *Proportions of USFS* lands (0.48).

Despite forecasted adopters in the *Northeast* having low proportions of USFS lands (<0.02) and low levels of NFP fuel treatments (0.08×10^6 m^2) on average, 40 counties were identified (28 likely and 12 most likely). These counties are incentivized to use biomass heating

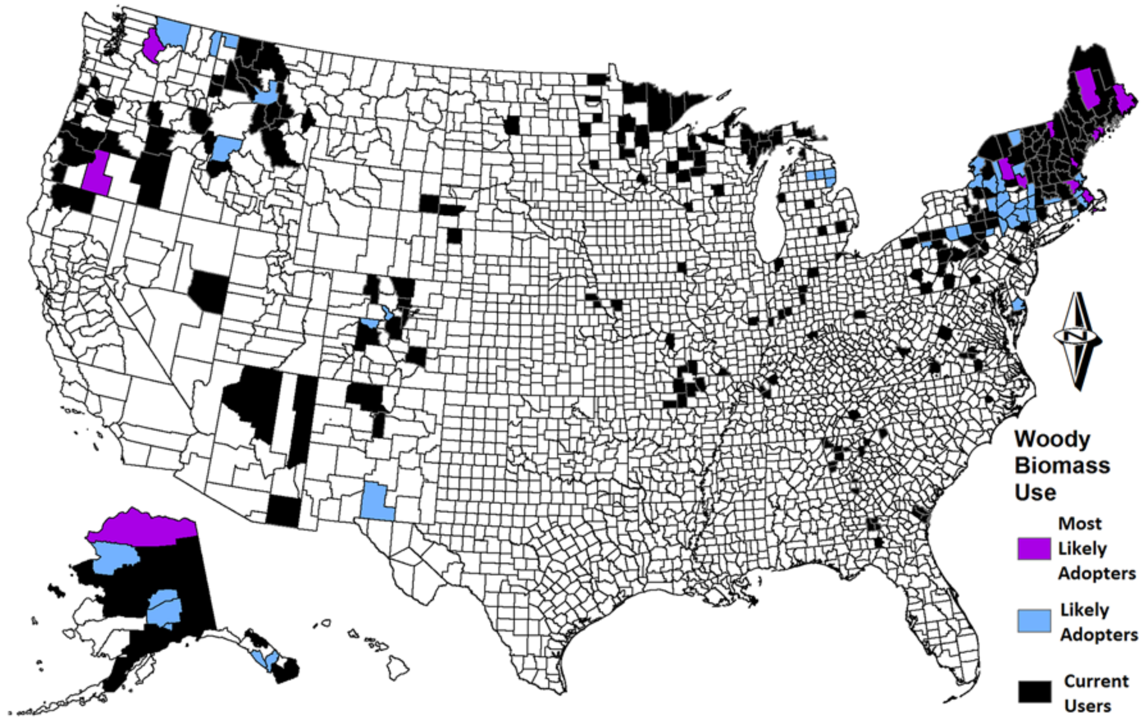

Fig. 3. County map of most likely adopters, likely adopters, and current users of institutional woody biomass heating based on Model 3. Current users are not differentiated by those selected or not selected for expansion.

by way of high heating costs ($12.63/1000 ft^3 of *Natural Gas*), and a vibrant wood products industry (3.71×10^7 m^3 of *Forest Residue*).

Other likely adopters include four counties in the *Lake States* region and three counties in the *Southwest*. When compared to the average forecasted adopter, these counties have less *Forest Residue* (1.98 and 0.67×10^7 m^3), and cheaper *Natural Gas* ($9.66 and $8.19/1000 ft^3). Likely adopters in Michigan of the *Lake States* region have lower average *Housing Prices* ($98,250), while adopting counties in Colorado of the *Southwest* have among the most expensive housing ($539,700) giving financial stability to incentivize the public's interest in renewable energy. Other incentivizing factors for likely adopters include high *Proportions of USFS* lands in both regions (0.43 and 0.65), and fuel-reducing treatments under the *NFP* in New Mexico of the *Southwest* (162.59×10^6 m^2).

5. Discussion

Within the context of location theory, all three principal location restrictions (physical, economic and technical) hold some influence on an institution's decision-making process when considering the installation of a biomass heating system. The successful deployment of biomass heating requires adoption locations that satisfy both physical restrictions (e.g. proximity to forest and active forest management) and economic restrictions (e.g. alternative energy prices and capital). Furthermore, the selection and installation of biomass heating is characterized by infrequent timing of installation, high upfront fixed capital costs with a long payback period, and new technologies with a limited history of deployment. For these reasons, increased scrutiny must be placed on the location of adopting institutions to make sure physical and economic restrictions are satisfied before technology and administrative processes are put in place to overcome any technical restrictions.

The models indicate that institutional adoption of woody biomass heating is greatly influenced by physical restrictions. Structural zeros are associated with a lack of institutional heating needs, or locally sourced biomass, while heating needs also influence the count of institutional users. As discussed in Section 3.1, the effective modeling of structural zeros with physical restrictions in the ZI model specification built a strong foundation for valid NB model estimations.

While physical restrictions effectively modeled the absence on institutional woody biomass heating systems, economic restrictions were strongly associated with the number of adopting institutions. The results show that lower natural gas prices attributable, in part, to increased production associated with hydraulic fracturing are likely to negatively affect adoption in areas where natural gas is available for heating. Additionally, adoption in counties with a lower socioeconomic standing would likely benefit from financial and technical assistance, especially when lower socioeconomic standing is concurrent with high primary road densities common in urban areas.

The models also suggest that rural attitudes towards biomass heating may outweigh costs associated with difficult terrain and challenging transportation logistics. Though roads are obviously required for biomass transportation at the national and regional scale, high road density may be indicative of suburban and urban areas that are less likely adopters of these systems.

There is also evidence that federal and state policies have an influence on the number woody biomass heating systems. In addition to the USFS generating a supply of fuel through national policy like the NFP, the USFS may also improve awareness and access to grant opportunities associated with USFS land management policy and programs, or it may be the effect of positive local attitudes towards wood heating practices that are usually associated with living close to actively managed timberlands.

The weak negative effect of aggregate U.S. state policies on institutions conflicts with expectations and prior results of Aguilar et al. (2011), who highlight policies as one of the potential driving forces for using woody biomass as a fuel source. After separating *Total Policies* by policy type there is some suggestive evidence that the presence of financial policies, such as project financing, may support biomass adoption by alleviating large start-up costs that take an extended period of time to recoup (Paepe et al., 2006). Conversely, procurement policies have a negative association on the progress of woody biomass heating systems, possibly due to ineffective targeting of decentralized woody biomass systems in favor of large facilities, or implementation of such policies in areas that have significant barriers to adoption. In general it appears that pro-biomass energy polices may not be effectively targeting small biomass heating systems, and are instead more focused on the manufacturing and utility sectors as supported by Becker et al. (2011). Accordingly, if an increase in institutional biomass heating capacity is a desirable policy outcome, it may require more coordinated, targeted and aggressive direct policies than have been implemented at the state level so far; potentially direct subsidies that help organizations finance installation of new systems.

It is worth noting that both federal land management practices and resources allocated to fuel treatments under NFP are highly subject to public policy decisions, including budget allocations for forest restoration and fuels treatments. Furthermore, there is some evidence that these treatments could more effectively target areas in the wildland-urban interface (Schoennagel et al., 2009). This could potentially lead to more available biomass adjacent to institutions that can use it for bioenergy, offsetting high treatment costs with revenues from harvest (Thompson and Anderson, 2015).

There are some limitations to the model and study design that ongoing research is already targeting. Potential negative effects on air quality are frequently cited by opponents of biomass energy systems. Using this analysis as a base case, the association with historic U.S. Environmental Protection Agency non-attainment areas and point source emissions with biomass heating adoption is currently being evaluated by the authors. Also, stakeholders at the institutional level could gain valuable knowledge from the inclusion of intra-institutional factors of adopting institutions. These include the effects associated with fuel sources of both the old fossil-fuel system and new woody biomass heating system, the number of employees tasked with boiler operations, and the area of heating space. For example, knowing which fossil fuels are most susceptible to substitution by woody biomass would help both institutions and governments refine their selection process for ideal adoption sites where efforts encouraging woody biomass heating systems are likely to be most effective and efficient.

6. Conclusions

This research has expanded the limited knowledge of policy effects and economic factors associated with institutional adoption of biomass heating systems, and can be used by key stakeholders to inform successful installation and operation of these systems. Using information provided by this study, individual institutions and communities can make informed decisions about the installation of biomass heating when the time comes to replace their current heating system.

This work should also be useful in guiding the development of effective public policy. The nuanced relationships between adoption and policy are among the most notable results. Among state policy instruments, financial policies appear to be most strongly associated with adoption. Financial assistance may help reduce risks associated with large up-front investment costs for institutions, and allow for additional flexibility when developing supply chain logistics and procuring biomass fuel over the life of the project.

Also, given the close connection between adoption and proximity to forest resources, future policy designed to incentivize decentralized use of biomass should consider land management polices at local, state and federal levels. If the goal of policy is to increase the adoption of biomass heating systems, policies that improve the health of local forests through active forest management should be considered, thereby providing a consistent supply of fuel. In addition, if biomass promotion through state land management policies is the desired policy instrument, it may be advantageous for states to better coordinate with federal land management, including treatments under NFP. Many states are already engaged in such coordination. Access to local federal personnel with knowledge of federal biomass projects and programs may also be important, but further research is needed to better understand such connections.

This research also provides an expansion map of counties with favorable environments for adoption that could be affected by changing market conditions. For example, counties where biomass removals are expected to increase under NFP could see a higher number of institutions using woody biomass heat. Likewise counties with increasing affluence or socioeconomic standing, or counties with state sponsored financing policies in support of small biomass heating systems may experience an increase in the rate of adoption. Conversely, areas with population growth or increasing urbanization may experience fewer institutions using biomass as the distance to active forest management increases. In addition, the expansion map can be used in concert with land cover data to determine what vegetation types are the most conducive to institutional use of biomass heating systems, with implicit ties to vegetation types that commonly produce timber, receive fuel treatments, or both.

Compared to centralized distribution systems for fossil fuels and energy, which are well established to provide heat and power to virtually all communities in the U.S., the current state of decentralized woody biomass heating systems is in its infancy, but growing. This analysis serves, in part, as a path forward by highlighting factors that are important when deciding what regions and counties of the U.S. are prime targets for the successful expansion of institutional wood heating. Undoubtedly, mature biomass and bioenergy markets can reduce the economic uncertainty that characterizes nascent markets, further catalyzing localized bioenergy expansion. This may further facilitate forest restoration and fuel reduction activities by providing new markets for the woody biomass byproducts of forest management. Though often precipitated by a need to lower heating costs, growth in this sector is likely to be tied to a complex interaction of economic, social, policy and ecological factors. At the center of this interaction are renewable energy, local economic development, and forest management.

Appendix A. Descriptive statistics for variables used in the models

Variable	Obs.	Mean	Std. dev.	Min.	Max.
Institutions	3142	0.128	0.676	0.000	16.000
Heating degree days	3142	4.997	2.192	0.002	19.095
Population density	3142	0.989	6.625	0.000	268.216
Natural gas prices	3142	10.431	1.830	7.380	35.187
House value	3142	131.799	80.438	0.000	944.100
Forest residues	3142	2.467	4.633	0.000	70.012
Biomass NFP	3142	2.416	12.811	0.000	250.929
Proportion federal lands[a]	3142	0.127	0.240	0.000	1.062
Proportion NPS	3142	0.007	0.044	0.000	1.000
Proportion FWS	3142	0.006	0.039	0.000	0.992
Proportion USFS[b]	3142	0.070	0.175	0.000	1.018

(continued on next page)

Appendix A (*continued*)

Variable	Obs.	Mean	Std. dev.	Min.	Max.
Proportion DOD	3142	0.009	0.034	0.000	0.742
Proportion BOR	3142	0.000	0.003	0.000	0.107
Proportion BLM	3142	0.020	0.090	0.000	0.952
Proportion BIA	3142	0.011	0.076	0.000	0.999
Total policies	3142	7.247	3.757	2.000	15.000
Cost share grants	3142	0.932	1.280	0.000	6.000
Technical assistance	3142	1.489	1.570	0.000	6.000
Financing	3142	0.544	0.675	0.000	3.000
Procurement	3142	1.306	1.026	0.000	4.000
Rules and regulations	3142	1.049	1.223	0.000	3.000
Tax incentives	3142	1.928	1.974	0.000	10.000
Population	3142	0.981	3.128	0.001	98.186
Road density	3142	0.204	0.199	0.000	2.650
Port capacity	3142	1.013	9.288	0.000	234.282
County area	3142	2.911	9.355	0.005	376.856
Latitude	3142	18.407	63.698	−126.638	433.385
Longitude	3142	34.470	104.920	−621.637	219.904
West Coast	3142	0.020	0.140	0.000	1.000
South	3142	0.259	0.438	0.000	1.000
Lake states	3142	0.105	0.307	0.000	1.000
Northeast	3142	0.078	0.268	0.000	1.000
Northwest	3142	0.072	0.259	0.000	1.000
Midwest	3142	0.255	0.436	0.000	1.000
Southwest	3142	0.050	0.219	0.000	1.000
Southern appalachia	3142	0.160	0.367	0.000	1.000

[a] Proportion of federal land exceeds one because the numerator contains both federal land area and inland federal waterways, while the denominator contains only federal land area. This has resulted in a proportion of federal land above one for the following 22 counties from the smallest to highest proportion: Unicoi, Tennessee; Ketchikan Gateway, Alaska; Mineral, Colorado; Mineral, Nevada; Graham, North Carolina; Ziebach, South Dakota; Leslie, Kentucky; Sitka, Alaska; Union, Georgia; Summit, Colorado; Macon, North Carolina; Aleutians West, Alaska; Rabun, Georgia; Menominee, Wisconsin; Osage, Oklahoma; Corson, South Dakota; Sioux, North Dakota; Wade Hampton, Alaska; Teton, Wyoming; Mahnomen, Minnesota; Dewey, South Dakota.

[b] Proportion of USFS land exceeds one for Wrangell, Alaska due to resolution differences in GIS data.

Appendix B. Likely adopting counties

Counties and residuals corresponding to Fig. 3, based on Model 3 in Table 4. Lowest (most likely to adopt) to highest (likely to adopt). This list does not include forecasted adopting counties that are currently using decentralized biomass heating systems in institutions.

County, state abbreviation	Residual	County, state abbreviation	Residual
North Slope Borough, Alaska	−6.672	Ulster County, New York	−0.689
Piscataquis County, Maine	−4.736	Essex County, Massachusetts	−0.680
Washington County, Maine	−4.378	Wayne County, Pennsylvania	−0.678
Klamath County, Oregon	−3.918	Oneida County, New York	−0.674
Strafford County, New Hampshire	−3.016	Sullivan County, New York	−0.660
Lincoln County, Maine	−2.765	Newport County, Rhode Island	−0.657
Knox County, Maine	−2.608	Denali Borough, Alaska	−0.654
Chelan County, Washington	−2.255	Otsego County, New York	−0.641
Nantucket County, Massachusetts	−2.228	Delaware County, New York	−0.631
Essex County, Vermont	−1.715	Rensselaer County, New York	−0.621
Middlesex County, Massachusetts	−1.154	Iosco County, Michigan	−0.612
Hamilton County, New York	−1.093	Bristol County, Rhode Island	−0.610
Saratoga County, New York	−1.035	Columbia County, New York	−0.604
Plymouth County, Massachusetts	−1.033	Tioga County, Pennsylvania	−0.603
Dukes County, Massachusetts	−1.016	Norfolk County, Massachusetts	−0.598
Anchorage Municipality, Alaska	−0.990	Wyoming County, Pennsylvania	−0.595
Warren County, New York	−0.952	Okanogan County, Washington	−0.583
Forest County, Pennsylvania	−0.951	Sussex County, Delaware	−0.583
Clinton County, New York	−0.929	Washington County, Rhode Island	−0.580
Summit County, Colorado	−0.894	Oscoda County, Michigan	−0.564
Pend Oreille County, Washington	−0.883	Boundary County, Idaho	−0.553
Northwest Arctic Borough, Alaska	−0.818	Crawford County, Michigan	−0.551
Hampden County, Massachusetts	−0.806	Potter County, Pennsylvania	−0.547
Pitkin County, Colorado	−0.789	Chenango County, New York	−0.544
Matanuska-Susitna Borough, Alaska	−0.783	Alcona County, Michigan	−0.539
Otero County, New Mexico	−0.770	Valley County, Idaho	−0.520
Missoula County, Montana	−0.758	Oswego County, New York	−0.518
Jefferson County, New York	−0.710	Petersburg Census Area, Alaska	−0.517
Dutchess County, New York	−0.704	Bristol County, Massachusetts	−0.510
Herkimer County, New York	−0.703	Greene County, New York	−0.505
Sitka City and Borough, Alaska	−0.697		

Appendix C. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eneco.2017.11.020.

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