Forest Policy and Economics 145 (2022) 102847

Contents lists available at ScienceDirect

Forest Policy and Economics

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

Wood bioenergy for rural energy resilience: Suitable site selection and potential economic impacts in Appalachian Kentucky

Kenton Sena [a], Thomas O. Ochuodho [b,*], Domena A. Agyeman [c], Marco Contreras [d], Chad Niman [b], Dan Eaton [b], Jian Yang [b]

[a] *Lewis Honors College, University of Kentucky, 1120 University Drive, Lexington, KY 40526, USA*
[b] *Department of Forestry and Natural Resources, University of Kentucky, 730 Rose Street, Lexington, KY 40546, USA*
[c] *Department of Agricultural Economics, University of Kentucky, Lexington, KY 40546, USA*
[d] *Instituto de Bosques y Sociedad, Facultad de Ciencias Forestales y Recursos Naturales, Universidad Austral de Chile, Campus Isla Teja, Valdivia, Los Ríos, Chile*

A R T I C L E I N F O

Keywords:
Forestry
Forest products
Residuals
Timber
Woody biomass

A B S T R A C T

Improving energy resilience, especially for rural communities, is a political, economic, and ecological priority, involving shifting energy portfolios away from fossil fuel dominance, reducing the environmental footprint of energy production and transmission, and localizing production and supply systems. In the Appalachian region, bioenergy systems, especially those involving woody biomass, may be key to improving energy resilience. However, because of its low population density and rugged topography, the region presents challenges to implementing biomass-based energy systems. This study was designed to identify critical infrastructure sites in Appalachian Kentucky with sufficient regional woody biomass supply to support reliable electricity generation. First, spatial analysis prioritized optimal biomass transportation distance, identifying 19 critical infrastructure sites in a region with feedstock supply suitable for a 100kWh unit, 4 of which were suitable for a 2MWh production unit. Second, economic analysis suggests that implementation of a woody biomass-based energy system in this region could have overall positive economic impacts. Future studies should elucidate in greater detail the local and regional economic impacts at each candidate site identified in this analysis, considering additional costs such as start-up and maintenance, and theoretical policy and incentive frameworks such as carbon emissions targets and subsidies.

1. Introduction

1.1. Energy resilience in rural communities

In a world facing climate change and associated increasing frequency of natural disasters, minimizing vulnerabilities of critical infrastructure is a high priority. “Energy resilience” addresses the need for dependable production and transmission of electricity, even in the face of devastating circumstances, such as natural disasters. According to McLellan et al. (2012), energy resilient communities have energy production infrastructure that meets the following criteria:

1) dependable, uninterrupted operation (or reliable backup operation),
2) not vulnerable to disasters,
3) capable of long-term operation without outside assistance (e.g., local supply chain and workforce),
4) easily shut off if not needed,
5) safe for humans and the environment, and
6) adaptable to meet dynamic energy needs (location, amount, and time).

While energy production and provision in the U.S. has historically been dominated by fossil fuels, Valentine (2011) observes that fossil-fuel-dependent energy infrastructure is increasingly non-resilient, faced with challenges of fuel (and waste) supply and cost. Due to their low population densities and remoteness (i.e., long electricity transmission distances), rural communities are vulnerable to disrupted power supply and are increasingly the focus of innovative decentralized community-based energy production and management systems to

* Corresponding author.
E-mail addresses: kenton.sena@uky.edu (K. Sena), thomas.ochuodho@uky.edu (T.O. Ochuodho), dagyeman27@vt.edu (D.A. Agyeman), marco.contreras@uach.cl (M. Contreras), chad.niman@uky.edu (C. Niman), jian.yang@uky.edu (J. Yang).

https://doi.org/10.1016/j.forpol.2022.102847
Received 11 July 2022; Received in revised form 15 September 2022; Accepted 17 September 2022
Available online 6 October 2022
1389-9341/

improve rural energy resilience (van Hoesen and Letendre, 2010; Hicks and Ison, 2011; Hoffman et al., 2013). Valentine (2011) highlights renewable energy as a priority sector for development of energy resilience, and the U.S. Department of Energy has placed particular emphasis on wood waste as a renewable energy feedstock (USDOE, 2004).

Sawmills produce a significant amount of waste, including coarse (e.g., chips, slabs, edgings, trims, cores), fine (sawdust, shavings) and bark residuals. Sawmills close to or vertically integrated with residual processing facilities (e.g., pellet plants, pulp and paper mills, etc.) have greater opportunity for marketing residuals, while transportation costs may be prohibitive for sawmills operating at a distance from such facilities. In 2015, Kentucky sawmills reported that over 56,600 m^3 of residuals went unused, composed of 5860 m^3 of bark, 4870 m^3 of coarse residuals, and 47,510 m^3 of fine residuals (USDA, 2018). Sawmills have limited space for stockpiling residuals on-site, and production can be hindered by over-accumulation of residuals; thus, convenient and economically viable disposal options for sawmills are essential. Mills with limited options for marketing residuals may be forced to pay disposal fees (e.g., landfill tipping fees) for unused residuals. Development of wood-residual-fired bioenergy production systems may present economic opportunity in these scenarios by mitigating disposal costs for sawmills.

In addition to energy vulnerabilities, rural areas often also suffer from economic vulnerabilities, including low job availability, high commute distance, and poor internet service. These difficulties are characteristic of the Appalachian region of the Eastern U.S, one of the most economically depressed regions in the country. In fiscal year 2022, the Appalachian Regional Commission (ARC) classified 39 Kentucky counties as among 81 economically distressed counties in the Appalachia (ARC, 2021). The economic situation in Appalachia is driven by the decline of the region's coal extraction and processing industry in recent decades (Freudenburg, 1992; McIlmoil and Hansen, 2010; Deaton and Niman, 2012). The region would benefit from economic diversification, and the bioenergy industry may present such economic opportunity (Law and McSweeney, 2013; Lobao et al., 2016; Taylor et al., 2017). Kentucky's rural communities, especially in Appalachian eastern Kentucky, are particularly needful of energy resiliency, and markets for residuals and low-quality wood. Community energy and economic resilience in Appalachian Kentucky may be improved if the high volumes of underutilized forest industry residuals are channeled into energy production.

1.2. Economic constraints and impacts of woody bioenergy

Successful establishment of bioenergy systems based on wood residuals is constrained by high biomass transportation costs, low existing electricity costs, competing markets for wood residuals, and high initial infrastructure establishment costs (van den Broek et al., 2001; Saidur et al., 2011; Espinoza et al., 2015). Alleviating any of these constraints can significantly improve the feasibility of the system. For example, transportation costs represented 21–33% of total delivered costs of biomass feedstock in a West Virginia study (Wu et al., 2011). Biomass transportation costs can be minimized by strategically locating bioenergy facilities with respect to standing timber slated for biomass harvest (Viana et al., 2010; Zambelli et al., 2012), or integrating with existing wood-based industry, such as sawmills, pulp, and paper (Korhonen et al., 2001; Andersson et al., 2006; Gavrilescu, 2008; Wetterlund et al., 2011; Murphy et al., 2015). Low electricity costs constraints can be overcome when renewable energy targets are mandated by policy (McIlveen-Wright et al., 2001).

Cost-effectiveness of wood-residual based bioenergy systems depends on availability of markets for wood residuals (i.e., chips, sawdust, and bark). Generally, woody bioenergy is less feasible when residuals markets are competitive (e.g., Junginger et al., 2001; van den Broek et al., 2001; Viana et al., 2010). However, when alternative markets are not competitive, such as when distances from sawmills to processing facilities present prohibitive transportation costs, sawmill residues are a waste product and a potential economic liability, and bioenergy markets can present opportunities to offset disposal costs (USDOE, 2004; Korhonen et al., 2001; Dornburg and Faaij, 2001; MacFarlane, 2009).

Feasibility of wood-fired bioenergy can be complicated by high startup costs and long payoff periods (Espinoza et al., 2015). Initial investment costs can be minimized by optimizing use of existing infrastructure, such as in co-firing wood biomass with coal in existing power plants (van den Broek et al., 2001; McGowin and Wiltsee, 1996; Hughes, 2000) and through policy-mandated subsidies (Leino et al., 2016). Additionally, while economies of scale support the implementation of larger units in some cases (Dornburg and Faaij, 2001), the use of small- and micro-scale units, such as combined heat and power units (CHP), are increasingly of interest to provide small-scale industrial heat and electricity demands while offsetting energy costs (Dong et al., 2009). These systems are more likely to be feasible when associated with a steady feedstock supply and consistent heating and power demands (Iakovou et al., 2010; Quesada-Pineda et al., 2016). Critical infrastructure, such as hospitals, could be priority sites for establishment of such resilient energy production infrastructure, given their high energy demand and need for uninterrupted power supply.

If these economic constraints can be alleviated, development of wood-based bioenergy is likely to have positive economic impacts. Perez-Verdin et al. (2008) found that the recovery of 4 million dry tons of woody biomass annually would create 585 direct jobs, 481 indirect jobs, and contribute $152 million of gross output to Mississippi's economy. In East Texas, Gan and Smith (2006) concluded that the electricity generation from woody biomass could generate about 1320 jobs and contribute about $352 million in total output. According to Saul et al. (2018), the development of forest-based bioenergy in the Northwest USA would contribute about $152 million annually and generate about 2.382 jobs in the region. In addition to economic impacts, renewable energy industry is associated with positive social impacts and increased social capital when compared to fossil-fuel based industry (Hicks and Ison, 2011; Evans et al., 2010).

1.3. Ecological impacts of woody bioenergy

Finally, development of bioenergy industry may present opportunity for positive ecological impacts in the central Appalachia hardwood region. The region's rich forests have experienced a shift in species composition over time, driven by resource extraction (Drummond and Loveland, 2010; Maxwell et al., 2012), poor management, and invasive species (Anagnostakis, 2001; Hansen et al., 2001; Clarke et al., 2016). These impacts have led to lower-value forests with increasing stocks of unmarketable timber. This high volume of standing unmarketable timber presents increased risk of devastating forest fires (Hudson, 2018), reduced forest ecological value, and reduced forest economic value.

For example, white oak (*Quercus alba*) has significant timber value and it is the only wood that can be used to make barrels for bourbon aging. The recent boom in the bourbon industry has increased pressure on standing white oak following increased demand for white oak barrels. However, managers and researchers have noted that white oak regeneration in forests is not keeping pace with demand and argue that woodland owners must employ intentional silviculture to promote white oak regeneration. While these practices can be economically infeasible for private forest landowners in Kentucky, markets for low-value standing timber may incentivize silvicultural practices leading to improved white oak regeneration, and improved overall ecological and economic value (Hjerpe and Kim, 2008; Catron et al., 2013).

The use of bioenergy also presents greenhouse gas emission benefits, reducing carbon emissions by offsetting fossil fuels with carbon-neutral biomass (MacFarlane, 2009; Hughes, 2000; Kelsey et al., 2014). In certain cases, bioenergy markets may support reforestation of marginal or underutilized land (Haddad et al., 2017; Huang et al., 2012). In the Appalachian region, an estimated 600,000 ha of currently unmanaged reclaimed surface mined lands could be reforested to support wood-based bioenergy and tremendous carbon sequestration (Zipper et al., 2011a; Zipper et al., 2011b; Amichev et al., 2008).

1.4. Policy as a driver of bioenergy implementation

As mentioned above, some of the economic barriers to implementing wood bioenergy can be alleviated through policy mechanisms to reduce startup costs or make bioenergy-based electricity more competitive economically (Leino et al., 2016; McIlveen-Wright et al., 2001). However, policy-driven changes in wood-based bioenergy markets can have unintended economic and ecological consequences. For example, Abt et al. (2010, 2012) found that regional policy mandating increased energy from renewable sources can increase competition for timber, if waste wood supply is exceeded, driving up timber prices. If scaled up to global implementation, as Raunikar et al. (2010) caution, large-scale and long-term increases in woody bioenergy implementation could drive up fuelwood prices until they reach parity with roundwood prices and begin diverting roundwood into energy markets. The economic effects of this would ripple through timber and timber products markets. Similarly, while wood bioenergy has been hailed as a “green” energy solution, and is expected to decrease net greenhouse gas emissions (Galik et al., 2015), others have noted that management for bioenergy could conflict with management for biodiversity conservation (Söderberg and Eckerberg, 2013), and still others note that bioenergy does not always lead to net decreases in emissions (Kallio et al., 2013). Thus, bioenergy policy should work to mitigate potential negative economic effects through prioritizing use of wood residuals and/or otherwise unmarketable timber, rather than roundwood, and minimize negative ecological effects by limiting incentives for bioenergy harvests from forests of conservation value and ensuring proper forest management (Sedjo and Tian, 2012), alongside community engagement (Shivan and Sayeed, 2010).

Based on US Energy Information Administration (EIA) data, total annual energy production from renewable sources in the US has increased steadily from 9.768 quadrillion BTU in 2015 to 12.320 quadrillion BTU in 2021 (US EIA, 2022a). The share of renewable energy production provided by biomass, however, has declined over the same period from 51.5% to 40.5%, as solar and wind sources become increasingly important in the renewable energy portfolio. Consistent with the decreasing share of total renewable energy provided by bioenergy, wood-based bioenergy in particular has declined from 23.7% of total renewable energy production in 2015 to 17.9% in 2021 (US EIA, 2022b). In January 2021, President Biden identified climate change mitigation as a central goal of his administration and outlined targets for clean energy technology development and implementation (Exec. Order No. 14008, 2021). Federal incentives for renewable energy development, including bioenergy development, are also a key component of the Inflation Reduction Act of 2022 (Inflation Reduction Act, 2022). In addition, as of 2020, 38 states and the District of Columbia had targets for renewable energy implementation, with several states planning for 100% renewable energy portfolios by 2045–2050 (DSIRE, 2020). Notably, several states in the southeastern US, including Kentucky, have not established renewable energy portfolio standards.

This study identified priority sites for potential establishment of wood-residuals fired CHP plants, as determined by proximity to both critical infrastructure sites (e.g., hospitals) requiring energy resilience and residuals production sites (e.g., sawmills) as a feedstock supplier. Once optimal sites were identified, this study investigated economic feasibility on a local scale, as well as economic impacts on a regional scale.

2. Research methods

2.1. Study area

The Appalachian counties of Kentucky (as designated by the Appalachian Regional Commission) with relatively homogeneous land cover (Bai et al., 2019) were selected as the target region for this study, which included: Bath, Bell, Boyd, Breathitt, Breathitt, Carter, Clark, Clay, Elliott, Estill, Floyd, Greenup, Harlan, Jackson, Johnson, Knott, Knox, Laurel, Lawrence, Lee, Leslie, Letcher, Madison, Magoffin, Martin, Menifee, Montgomery, Morgan, Owsley, Perry, Pike, Powell, Rockcastle, Rowan, Whitley, and Wolfe. These 36 counties have a thriving forest industry, with many primary forest industry facilities spread across the region. These counties are also mostly rural and mostly impoverished, thus meeting project criteria for investigating economic and energy resilience.

2.2. Critical infrastructure

Critical infrastructure facilities, including hospitals and emergency services (e.g., police, fire, Emergency Medical Services) were selected as potential sites for establishment of a wood-fired CHP unit. These facilities were selected because of their need for reliable, uninterrupted energy supply. Location (coordinates and address) data for critical infrastructure facilities were obtained from the Emergency Personnel Location Route Finder project (https://loggingeplroutes.ca.uky.edu/). Because of their high-power demand, hospitals were prioritized for further analysis. Annual electricity usage for hospitals was estimated as follows: number of beds in each hospital were accessed through the Kentucky Geonet database (DGI 2018), then hospital building area (m^2) was estimated from number of beds using a conversion factor of 230 m^2 per bed (Fricke, 2017) and converted to estimated energy consumption using an estimated 270 kWh/m^2 (Grumman/Butkus Associates, 2017).

2.3. Sawmill locations and residuals production

The University of Kentucky Forestry Extension Service and Kentucky Division of Forestry cooperatively maintain a database of primary and secondary wood industry facilities in Kentucky (https://forestry.ca.uky.edu/wood-directory). This database includes facility locations and self-reported timber product outputs. Primary forest industry facilities (sawmills) within the study region were selected from this database. Sawmills with lumber drying kilns were excluded from the study because wood residuals are typically consumed onsite. Some sawmills did not report residuals production; for each of these facilities, residuals production was estimated as the average residuals production from reporting sawmills of the same production level.

2.4. Standing unmarketable biomass

In addition to wood industry residual production, available biomass as standing unmarketable timber (i.e., low-grade) was estimated using the USDA Forest Service Forest Inventory Analysis (FIA) data (US Department of Agriculture (UDSA), 2019). If a CHP unit was established at a given site, standing unmarketable biomass may provide an important buffer to biomass supply, ensuring constant and adequate biomass feedstock availability (Iakovou et al., 2010). To estimate available biomass of unmarketable timber, FIA survey data from one complete survey cycle (trees inventoried between 2000 and 2004) were analyzed. Briefly, for each plot in the study region, trees <12.5 in. DBH and trees classified as “rough cull” or “rotten cull” were identified as unmarketable timber. While not all trees <12.5 in. DBH will be truly unmarketable (e.g., some will be young trees of desirable hardwood species), the understory and midstory of Appalachian forests is often dominated by undesirable or unmarketable species that must be removed to release more valuable species, such as oaks (Abrams, 2003). Biomass of unmarketable trees was estimated for each plot and expressed as a percentage of total biomass. These low-grade estimates were scaled up to the county level by averaging % low-grade biomass across the plots within each county (finest possible scale, because USFS uses "fuzzy" location coordinates for each plot). Using the USDA Forest Service biomass raster (Blackard et al., 2008; USDA-FS, 2019), which reports biomass in Mg/ha for each 250 m^2 cell, total biomass (Mg) was calculated for each cell. Then, for each county, the total biomass per cell was converted to estimated unmarketable biomass per cell by multiplying by the average % unmarketable biomass for the given county. The total available unmarketable biomass (618,000 metric green tons, or 309,000 metric dry tons) for the study region was calculated by summing the estimated available biomass in each cell within the region, and this value was used for region-wide economic analyses as described below.

While we estimated the biomass of standing unmarketable timber, we emphasize that our downstream analysis identifying priority sites for establishing a wood-fired bioenergy unit was based on residuals availability and proximity—standing unmarketable timber was treated as a supplemental fuel only. As described above, policy increasing bioenergy production can have unintended consequences for forest conservation and timber and timber products markets—we believe that our focus on otherwise unused residuals as a feedstock mitigates these unintended consequences.

2.5. Transportation costs

Because transportation cost is one of the greatest constraints on bioenergy feasibility, transportation distance and time from point of residual production (sawmill) to nearest point of combustion (e.g., theoretical CHP unit on site at a hospital) was estimated. Transportation distance and time estimates were obtained by sending requests to Google's Distance Matrix API (application programming interface). Each request included the origin address (mill location in latitude and longitude) and the destination address (critical infrastructure latitude and longitude). The JSON (JavaScript Object Notation) responses from the distance matrix API were parsed to retrieve distance and travel time. Estimated transportation costs were calculated from travel time, assuming a truck rental rate of $80/h (Conrad and Joseph, 2018). Transportation costs for standing unmarketable biomass were estimated using a similar approach: available unmarketable biomass was scaled up to 1000 m^2 cells, and transportation distance and time were estimated from the center of each cell to the nearest infrastructure facility, using Google's distance matrix API, as described above.

2.6. Biomass feedstock supply estimates

Two candidate CHP units were selected to model annual feedstock supply requirements under two power supply scenarios—100 kW and 2 MW. Assuming that installation of a CHP unit would only make sense for facilities with high enough power demands to warrant consistent operation, facilities using enough power to run a CHP unit for at least 5 days per week were selected. Power production and associated biomass consumption rates were estimated using data from King (King, 2014) for these scenarios. For the 100 kW CHP unit, 3029 bdt of biomass were required to produce 876 MWh yr^{-1}, resulting in 289.2 kWh yr^{-1} per bdt. On the other hand, the 2 MW CHP unit required 19,089 bdt of biomass to produce 17,520 MWh yr^{-1}, thus resulting in a much higher energy generation efficiency of 917.8 kWh yr^{-1} per bdt. Next, the ten closest sawmills to each facility were identified. Annual residuals production (bdt) for each of these sawmills was converted to truckloads of biomass using the conversion factor (23.6 bdt/truckload). The system was assumed to be economically infeasible if the cost of shipping biomass from point of origin (e.g., sawmills) to point of combustion (e.g., hospital) exceeded the cost of purchasing the same amount of electricity from the grid, estimated based on average electricity prices of $0.0873/kwh. The system was also assumed to be infeasible if the neighborhood biomass supply (e.g., biomass from the 10 nearest mills) was insufficient to meet minimum operating thresholds (5 days/week operation).

2.7. Regional economic impacts analysis

Region-wide economic impacts of establishment of wood-based bioenergy systems were modeled using computable general equilibrium (CGE) models. CGE models have been widely employed to study economy-wide impacts of natural resource policies because of their many advantages over other analytical tools (Gillespie et al., 2001; Rickman, 1992; Robinson and Roland-Holst, 1988). CGE models are a class of economic models that use economic data, usually in the form of an input-output table or social accounting matrix (SAM), to estimate how an economy might react to changes in investments, policies, markets, technologies, or other such factors (Miller and Spencer, 1977; Shoven and Whalley, 1972; Johansen, 1960). CGE models endogenize the price and demand system; enable substitution in production and demand; provide a more realistic treatment of factor scarcity, institutions, and the macroeconomic environment; and allow for optimization of agent behavior (Banerjee and Alavalapati, 2010, 2014). CGE models can capture in detail sectoral reactions and the resulting structural changes and feedback effects. Because of these characteristics, CGE models are well-suited for the study of bioenergy development and policies (Haddad et al., 2017; Huang et al., 2012; Furtenback, 2011; Lu et al., 2010; Laitner et al., 2006; Binkley et al., 1994; Bergman, 1988).

2.7.1. Theoretical CGE model

This study used a CGE model originally developed by Lofgren et al., 2002 and later customized by Holland et al. (2007) to be compatible with the IMPLAN (IMpact analysis for PLANning) dataset. The model is deterministic in nature with assumptions of small-open-economy and constant returns to scale technology. Producers maximize profits subject to constant returns to scale technology with three factors of production (labor, capital, and land). Households, government, and the rest of the world (and rest of the U.S. separately) are the major institutions in the model. Households consume different commodities through maximization of a Stone-Geary Utility function (a Linear Expenditure System (LES) function) subject to its disposable income constraint (Stone, 1954). Fig. 1 shows the production structure of the model.

Consumer demand between domestic and imported goods is determined through a constant elasticity of substitution (CES) Armington specification (Armington, 1969). The Armington specification allows consumers to discriminate between domestically produced and imported goods. The CES function assumes domestic and imported goods are imperfect substitutes. Each sector produces a composite commodity that is transformed through a constant elasticity of transformation (CET) function into a commodity sold on the domestic market or exported. The CET function assumes imperfect substitutability between products produced for the domestic and export market. As is routine with any CGE model, standard closure rules specifications are employed to achieve equilibrium in all markets. The model was solved using the General Algebraic Modeling System (GAMS) software as a Mixed Complementary Problem (MCP) using the PATH solver (GAMS, 2012). Detailed model description is in Supplementary Information file attached separately with model sets, parameters, equations, variables, and equations.

2.7.2. Database and CGE model calibration

SAM is the basic accounting structure and data required to implement a CGE model. A SAM is a comprehensive statistical representation of an economy at a particular point in time, usually one year. It is a square matrix with matching row and column accounts, where each cell in the matrix shows a payment from its column account to its row account. Major accounts in a standard SAM are the following: activities that carry out production; commodities (goods and services) that are produced or imported and sold domestically or exported; factors used in production (labor, capital, land, and other natural resources); and

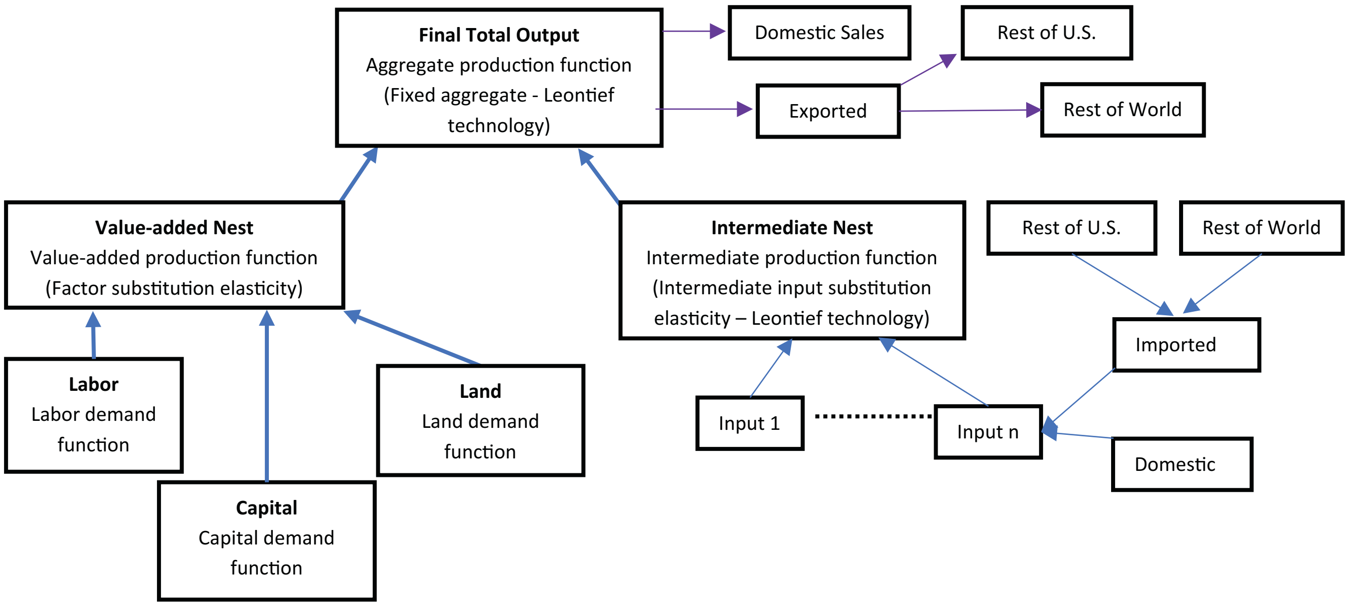

Fig. 1. Production technology tree for regional CGE model in U.S. (Authors' illustration).

institutions such as households, government, and the rest of the world (Pyatt and Round, 1985; UN, 2008). The Eastern Kentucky SAM dataset for this project was purchased from Minnesota Implan Group (IMPLAN) that produces annual SAM data by county. Other required data and parameters (such as elasticities) for the CGE model were obtained from literature sources.

The SAM database used for this study is the 2017 baseline aggregate of the IMPLAN dataset for the 36 eastern Kentucky counties in the study region, which has 332 total industries (sectors) out of 536 potential total industries. To narrow down to the sectors of interest for this analysis, the 332 sectors present in the regional SAM were aggregated into 12 sectors using sectoral mapping and aggregator algorithms in GAMS: agriculture, logging, bioenergy electricity generation, all other electricity generation, electric power transmission and distribution, natural gas distribution, coal mining, wood products manufacturing, transportation, other manufacturing, services, and the rest of the economy. Due to space limitation, we cannot present the sectoral aggregation scheme here, but this is available upon request. A summary of 2017 SAM of the study region is presented in Table 1.

Before 2015, electricity generation (2015 IMPLAN industry code 41) was not broken down by sources of its contributing commodities in the Industry by Commodity account in the IMPLAN database. This made isolating electricity production from biomass under the Industry by Commodity account a challenging task. However, beginning with the 2015 dataset, even though electric power generation by sources are not defined as unique commodity accounts, they are presented under the social account balance sheet from which one can create a unique SAM. Based on the 2017 IMPLAN database for the study region, electric power generation from biomass (commodity code 3047) as intermediate input is not reported.

CGE model is a comparative analysis, where the impact is the difference between the after-shock (counterfactual) level and initial (baseline) level. Fig. 2 is a flow chart of the CGE modeling process and experiment as was implemented in this study.

Initial (baseline) reference levels of intermediate biomass demand for electric power production and bioenergy production (total output) were required. Given that the regional SAM database reported zero levels of these, we used the next-best available reference point. We assumed that the study region had a similar share (of total energy production) of bioenergy production levels as those reported for the entire state of Kentucky. Renewable resources are a relatively small part of

Table 1
Eastern Kentucky 2017 SAM Summary.

Model Information			
Model Year	2017	Value Added	
GRP (GDP)	$24,564,794,160	Employee Compensation	$13,895,269,128
Total Personal Income	$27,052,150,000	Proprietor Income	$1,147,785,546
Total Employment	356,444	Other Property Type Income	$7,638,859,007
		Tax on Production and Import	$1,882,880,479
Number of Industries	332		
Land Area (Sq. Miles)	11,817	Total Value Added:	$24,564,794,160
Area Count (Counties)	35		
		Final Demand	
Population	851,459	Households	25,991,130,080
Total Households	339,279	State/Local Government	$4,872,829,048
Average Household Income	$79,734	Federal Government	$973,679,674
		Capital	$5,282,147,607
Trade Flows Method	Trade Flows Model	Exports	$21,838,934,660
Model Status	Social Accounts	Imports	($33,279,184,404)
		Institutional Sales	($1,114,742,305)
Economic Indicators			
Shannon-Weaver Index:	0.7397	Total Final Demand:	$24,564,794,361

Note: Totals of value added may not equal to final demand due to rounding off.

Kentucky's energy mix, and the state has no renewable energy standard (Durkay, 2019). About one-tenth of the renewable generation in Kentucky, 0.6% of the state's total net generation, comes from biomass (U.S. EIA, 2019a). Consequently, we assumed a bioenergy baseline of 0.6% of total electric energy production for the study region for 2017.

With the commodity output values available from the IMPLAN, the intermediate and primary factor input demand for the bioenergy sector was estimated for the 12 aggregated SAM sectors according to share

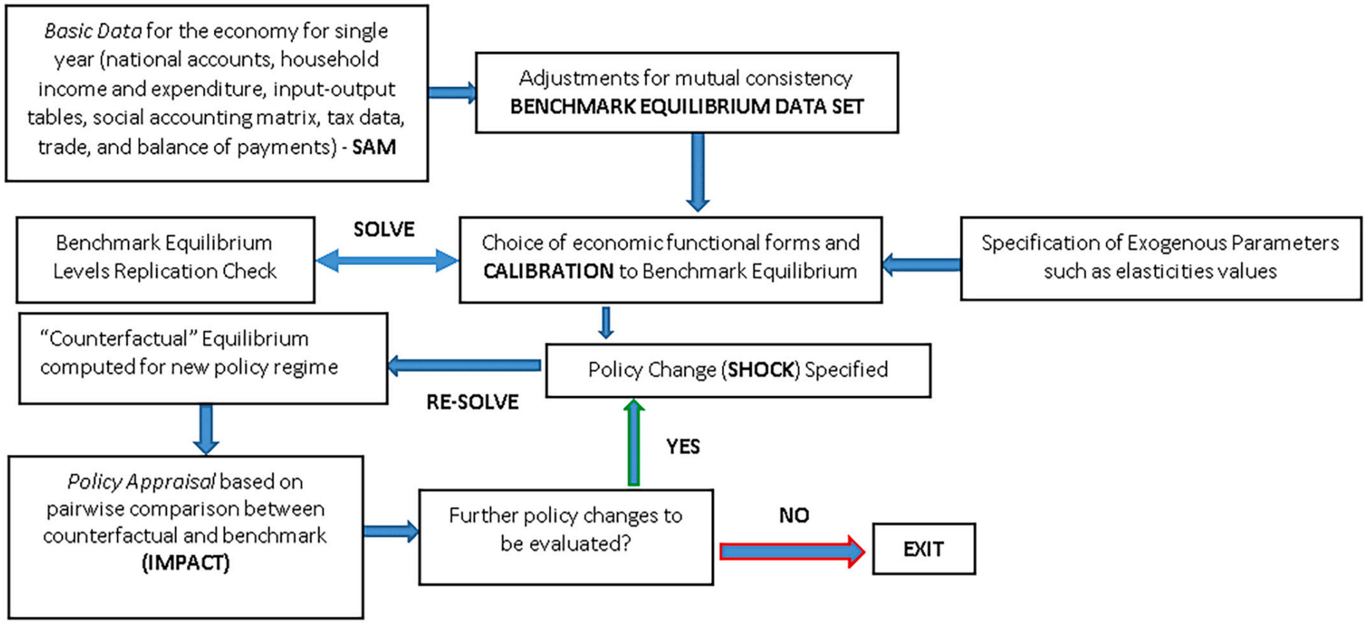

Fig. 2. Flow chart of the CGE modeling process and experiment (Modified from Shoven and Whalley, 1984 pg 1019).

ratios (Taheripour et al., 2010; Winston, 2009; Ochuodho et al., 2019). The 2017 IMPLAN database has nine household income classes. To capture welfare impacts of our analysis at the household level by annual income categories, and for simplicity, the households are aggregated into three groups: low income (annual income less than \$15,000 to \$40,000), middle income (\$40,000 to \$100,000), and high income (greater than \$100,000). Total input-output (row and column sums) imbalances were created in the process of creating the bioenergy sector from IMPLAN database. The cross-entropy procedure using GAMS algorithms was used to produce a balanced final SAM (Robinson and El-Said, 2000; Robinson et al., 2001).

Equivalent variation (EV) is used as welfare measure in this study. Equivalent variation is a measure of both price and income effects. It represents the change in household income at current prices that a change in prices would have on household welfare if income were held constant at initial level prior to any shock in the economy. It is the amount of income that a consumer would have to be compensated with so as to make the consumer well-off in case the economic shock was to take place. Gross Domestic Product (GDP) is estimated at market prices. Briefly, GDP is the total of all goods and services produced in an economy. GDP can be estimated based on factor/input cost that is needed to produce goods and services in an economy. This is termed as GDP at factor cost. GDP can also be estimated based on the gross value at market prices of all goods and services produced by an economy plus taxes but minus subsidies on imports. This is referred to as GDP at market prices.

2.7.3. *Experimental shock scenarios*

As described above, total available biomass (from standing unmarketable timber) that can be potentially exploited cost-effectively for bioenergy production in the study area was assessed to be about 618,000 metric green tons (309,000 metric dry tons). The economic viability for bioenergy production from wood biomass is directly affected by among other factors, price of biomass (dry or green). This biomass translates to about \$37.9 million at an average price of \$122.62 per metric dry ton in the U.S. South (Statista, 2019).

U.S. electricity generation from biomass across all sectors grew from 56 terawatt hours (TWh) in 2010 to 64 TWh in 2015. Much of this growth occurred in southern states such as Virginia, Florida, and Georgia. In 2015, electricity generation from biomass across all sectors accounted for 11.3% of renewable electricity generation and 1.6% of total electricity generation in the United States (U.S. EIA, 2019b). Nearly half of the electricity generated from biomass in 2015 was at industrial facilities outside of the electric power sector, such as pulp and paper mills. Within the electric power sector, biomass accounted for 6.3% of renewable electricity and 0.8% of total U.S. electricity generation (U.S. EIA, 2019b). In 2017, U.S. renewable energy consumption stood at 12.7% of total of which 45% was from biomass (of which biomass waste, 4%; biofuels, 22%; wood, 19%) (US EIA, 2019c). This implies that biomass waste and wood biomass contributed total of 1.9% of total energy consumed.

As noted earlier, Kentucky ranks low among the states with respect to the share of its energy portfolio produced by renewable energy sources. Therefore, even with available biomass that can be economically exploited for bioenergy production in the study region (309,000 metric dry tons), there are still structural, market, and capacity barriers that would hinder sudden bioenergy production. Without real and specific economic or policy stimulus, it is difficult to simulate and assess specific levels of increased use of biomass for bioenergy production. We set up two experimental shock scenarios as follows:

(i) Three levels of increased intermediate demands for wood biomass for bioenergy production (by increasing the share of bioenergy in electric power production with broad assumptions of existing capacities and infrastructures):

- Low: 50% increase from initial baseline
- Medium: 100% increase from initial baseline
- High: 138% increase from initial baseline

These three levels of increased intermediate demand of biomass for bioenergy production increase share of bioenergy in electric power production to 0.9, 1.2, and 1.4%, respectively. These shares are in the ballpark of national averages and therefore not very hypothetical.

(ii) Three levels of increased tariff rates (indirect business tax rate in the model) on non-bioenergy-sourced electricity production (to incentivize reduced demand for non-renewable energy production):

- Low: 5% increase from initial baseline

- Medium: 10% increase from initial baseline
- High: 20% increase from initial baseline

The CGE model has been specified to enable simulation of various scenarios, following specific policy and market triggers, including:

- Biomass transportation costs
- Prices of other energy alternatives such as coal and natural gas
- Price of electricity and electricity tariff rates
- Increased demand of bioenergy relative to other energy sources
- Renewable portfolio standards (RPS)
- Increase indirect business taxes on non-bioenergy-sourced electricity

While the model can simulate these scenarios, these should be done in context of specific policy and market scenarios. Hypothetical simulations may not produce any valuable information as they will not be specific to a situation.

3. Results

3.1. Spatial analysis

A total of 51 medical facilities were identified in the study area, and the spatial analysis identified 19 eastern Kentucky hospitals as candidate sites for establishment of a 100 kW wood-fired CHP unit, four of which were also candidates for a 2 MW CHP unit (Fig. 3).

For the 19 selected hospitals, energy consumption ranged from 36,450 to 4725 MWh yr^{-1}, resulting in associated annual expenditures from 3.18 to 0.41 US$ millions (Table 2). The amount of biomass residuals available from the ten closest mills to these 19 hospitals (some of which are the same for different hospitals) on average was 201,514 bdt yr^{-1}, ranging from 132,926 to 274,126 bdt yr^{-1}. Based on the power generation of 100 kW CHP, the number of units required to supply all consumption ranged from 41.6 to 5.4 units for the largest and smallest hospital. Based on proximity to each hospital, on average it was economically efficient to transport and use the available residuals from the six closest mills to supply all energy consumption (Table 2). However, for hospital 16 for example, available residuals from the closest

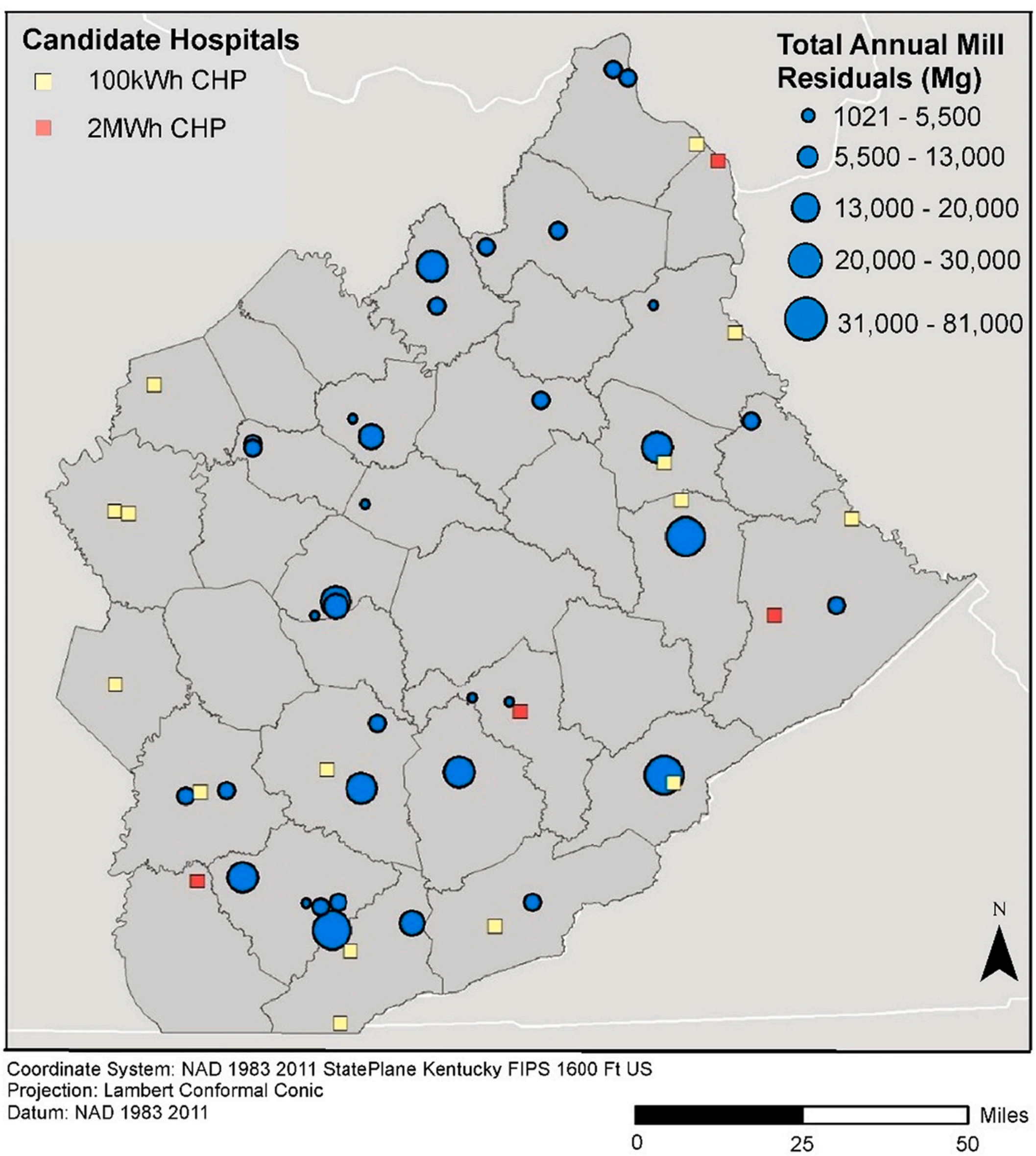

Fig. 3. Hospitals identified as candidate sites for establishment of wood-fired CHP units, based on neighborhood wood residual availability.

Table 2
Summary of spatial analysis results of selected hospitals wherein to establish CHP units.

Hospital ID	Energy consumption	Energy Cost	Residuals available from the ten closest mills	100 kW CHP units: N° of units to supply consumption	Number of mills required to supply biomass	Economically feasible biomass to use from ten closest mills	Total biomass transportation cost	Total savings	2 MW CHP units: N° of units to supply consumption	Proportion biomass used from ten closest mills	Economically feasible biomass to use from ten closest mills	Total biomass transportation cost	Total savings
	MWh yr^{-1}	US$ yr^{-1}	bdt			bdt	US$ yr^{-1}	US$ yr^{-1}			bdt	US$ yr^{-1}	US$ yr^{-1}
1	36,450	3,182,085	248,633	41.6	7.71	132,231	321,920	2,860,165	2.1	2.42	35,032	68,177	3,113,908
2	26,850	2,344,005	141,869	30.7	8.05	110,106	272,838	2,071,167	1.5	4.45	38,632	76,687	2,267,318
3	23,250	2,029,725	171,610	26.5	6.85	146,903	497,259	1,532,466	1.3	1.44	32,209	79,101	1,950,624
4	20,475	1,787,468	271,371	23.4	4.72	164,940	250,605	1,536,863	1.2	2.36	31,021	29,690	1,757,778
5	11,325	988,673	274,192	12.9	2.68	138,022	146,176	842,496					
6	11,250	982,125	158,591	12.8	8.70	135,011	351,720	630,405					
7	11,250	982,125	136,698	12.8	7.08	116,381	156,959	825,166					
8	11,025	962,483	262,307	12.6	4.86	168,909	349,918	612,564					
9	9450	824,985	141,869	10.8	8.05	110,106	267,209	557,776					
10	9225	805,343	161,462	10.5	6.04	71,819	171,039	634,303					
11	9000	785,700	156,127	10.3	6.43	123,793	162,215	623,485					
12	7875	687,488	250,974	9.0	5.82	140,220	274,010	413,477					
13	7687	671,075	250,974	8.8	4.65	132,620	374,653	296,422					
14	6750	589,275	248,607	7.7	3.31	102,888	162,142	427,133					
15	6750	589,275	156,712	7.7	5.02	69,138	170,471	418,804					
16	5925	517,253	132,926	6.8	9.51	126,317	268,400	248,853					
17	5475	477,968	219,572	6.3	4.50	126,158	319,424	158,543					
18	5400	471,420	186,070	6.2	5.27	121,031	245,433	225,987					
19	4725	412,493	258,207	5.4	4.69	146,912	205,208	207,285					
Average	12,112	1,057,419	201,514	13.8	6.01	125,448	261,452	795,966	1.5	2,67	34,223	63,413	2,272,407

nine mills and 51% of the available residuals from the tenth closest mill are needed to supply energy consumption. On the other hand, for hospital 5, residuals from the three closest mills are needed and only 68% of those from the third closest. The amount of residuals economically feasible to transport to the selected hospitals was on average 125,448 bdt (range 168,909–9138 bdt) with an average transportation cost of 261,452 US$ yr^{-1} (range 497,259–146,176 US$ yr^{-1}), and an average annual saving of US$ 795,996.

For hospitals 1–4, which were also candidates for establishing the larger 2 MW CHP unit, the number of units needed to produce all required energy consumption was lower due to the higher energy generation efficiency. However, because of the higher biomass requirements to operate at least five days a week, only these four hospitals are sizable enough. Although for several of the smaller hospitals it is economically efficient to use the biomass of some mills, that amount is not enough to run the 2 MW CHP unit for less than five days a week. For these four selected hospitals, on average 1.5 CHP units are required to supply all energy consumption using residuals from the three closest mills, which provide 34,223 bdt annually with a transportation cost of US$63,413 and annual savings of about 2.27 million US$. Worth noting is that these savings consider only transportation cost and ignore the CHP unit establishment and operating costs.

These analyses indicate that these hospitals are located sufficiently close to area sawmills with sufficient wood residuals production to permit relatively low-cost biomass transportation. Because this is one of the primary barriers to successful bioenergy implementation, this analysis is critical for identifying candidate sites for more detailed economic feasibility studies.

In the event that a CHP unit was established at a given site, standing unmarketable biomass may provide an important buffer to biomass supply, ensuring constant and adequate biomass feedstock availability in the event of any disruption to feedstock supply from area sawmills (Iakovou et al., 2010). Our analysis found that forests in this region are, in some cases, dominated by unmarketable, low-grade timber (Fig. 4). While these low-grade materials may be of insufficient quality for most standard timber applications, they could be marketed as bioenergy feedstock material under appropriate market conditions. Thus, development of wood-based bioenergy markets in the region could subsidize the costs of forest management for private woodland owners, landowning corporations, and federal and state agencies managing public lands.

3.2. Economic analysis

Economy-wide impacts in CGE models are generated from the general equilibrium condition. For this reason, we cannot present impacts on all variables (412) for all sectors (12) here. We therefore present summarized results on key micro- and macro-economic indicators, including net household income, regional gross product (GDP), and household social welfare. These economic indicators represent the overall aggregate impacts of prices and quantities of intermediate demand/supply, final demand, value-added, and total output in all sectors of the economy. Tables 2–4 summarize the economy-wide impacts on net household income, gross regional product, and household social welfare, respectively. The impacts are in dollar values with percentage changes in parentheses to highlight the level of impact.

Out of the 339,279 households; 189,279, 114,623, and 35,547 were classified under low, middle, and high-income households, respectively. The estimated impacts reveal increase in net income of all household categories. Moreover, low-income households experience the lowest increase in net income with percentage increase of 0.0005, 0.0011, and 0.0024% under low, medium, and high scenarios, respectively. Projected net income impact is highest for middle income households under all three scenarios. However, percentage increases in net income from the baseline are slightly lower than what is observed for high income households. Broadly, these impacts indicate that expanding the use of

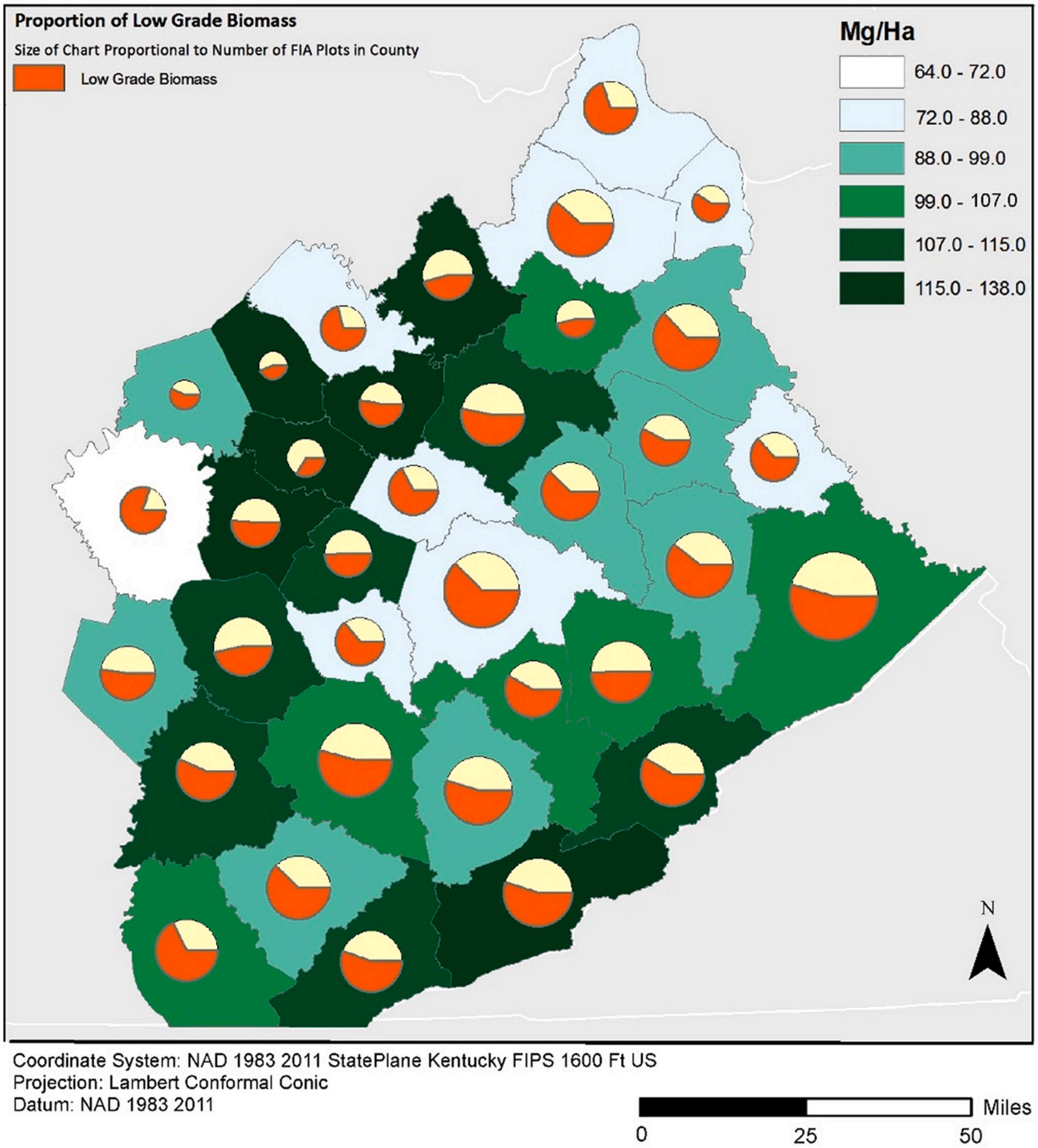

Fig. 4. Standing unmarketable (low-grade) biomass potentially available as supplemental feedstock supply to support wood-based bioenergy. Approximately 423,000 private individuals own 78% of Kentucky's timberland, while corporations own 13% (including 2% owned by forest industry). Nine percent is publicly owned (including 5% in national forests) (Butler et al., 2021).

Table 3
Projected net household income in dollars*, with % change from baseline indicated in parentheses, under modeled scenarios (increased intermediate demand of biomass for bioenergy production and increased tariff rates on non-bioenergy-sourced electricity production).

Household annual income category	Number of households (% of total)	Modeled Scenarios		
		Low	Medium	High
Low $0-40 K	189,623 (56)	50,186 (0.0005)	100,503 (0.0011)	223,824 (0.0024)
Medium $40-100 K	114,110 (34)	153,582 (0.0016)	307,548 (0.0032)	678,991 (0.0071)
High > $100 K	35,547 (10)	108,938 (0.0021)	218,126 (0.0041)	475,207 (0.0090)

* net of income taxes, savings, inter-household transfers, and overseas transfers.

Table 4
Projected Gross Domestic Product (GDP) in dollars, with % change from baseline indicated in parenthesis, under modeled scenarios (increased intermediate demand of biomass for bioenergy production, as well as increased tariff rates on non-bioenergy-sourced electricity production).

GDP Type	Modeled Scenarios		
	Low	Medium	High
GDP at market prices (regional GDP)	1,265,545 (0.0052)	2,532,202 (0.0103)	5,270,277 (0.0215)

wood biomass for bioenergy production or increasing demand for bioenergy in electric power generation at the expense of non-bioenergy-sourced electricity production in rural Kentucky would benefit richer households more than poorer households.

The reported impacts in Table 4 are based on Gross Domestic Product (GDP) at the market prices. As expected, estimated GDP impacts increased from the low scenario to the high scenario but the percentage change under each scenario was modest. For instance, under the high scenario, 138% increase in intermediate demand for wood biomass for bioenergy production coupled with 20% increase in tariff rates on non-bioenergy-sourced electricity production increased regional GDP by 0.00215%. In a respective order, regional GDP increased by $1,265,545, $2,532,202, and $5,270,277 under low, medium, and high scenarios, respectively. These values represent marginal percentage increase of 0.0052, 0.0103, and 0.0215%, respectively under low, medium, and high scenarios.

Household welfare is measured by equivalent variation in dollars. Welfare impacts increase with increased intermediate demand of biomass for bioenergy production and increased tariff rates on non-bioenergy-sourced electricity production. However, this benefit tended to tilt more towards medium and high-income households, which, despite their lower proportion, get a larger share of the benefits than the low-income category households (Table 4). For all simulated scenarios, middle-income households received the highest welfare benefits among the three household categories. For example, under the high scenario, middle income households received increase welfare impacts of $740,902 followed by high-income households and low-income households who received $508,064, and $285,770, respectively. This raises issues of equity. Estimated welfare impacts ranged from $68,613 for the low-income households to $740,902 for the middle-income households. It is observed that household utility in the study region increased marginally, ranging from 0.0001% to 0.001% with middle income and high-income households experiencing the highest increase in utility (Table 5).

4. Discussion

4.1. Spatial analysis

The spatial analysis identified 19 eastern Kentucky hospitals as potentially suitable sites for establishing a 100 kW wood-biomass fired CHP unit, four of which were also considered suitable for a larger 2 MW unit. This analysis considered some of the most important factors relevant for successful wood-bioenergy systems, such as electricity cost, transportation distance, and potential feedstock supply, and provides critical foundational information supporting further site-specific analyses capable of incorporating additional impactful variables (e.g., alternative markets for wood industry residuals, infrastructure costs, and cost-share programs). Importantly, this analysis identified significant biomass feedstock availability in standing unmarketable timber. This unmarketable timber resource represents both a barrier and an opportunity—unmarketable standing timber competes with marketable timber for resources, especially light, and must be physically removed from the forest to support the growth of desired marketable species. For private landowners, this timber stand improvement can be cost-prohibitive. Cost-sharing or subsidy programs can help alleviate this cost barrier (Ovaskainen et al., 2006, 2017; Wang et al., 2021), but developing a biomass market for otherwise unusable standing timber could also successfully transform this challenge into an economic opportunity (Dulys-Nusbaum et al., 2019). As of March 2022, the average price for roundwood or pulpwood as biomass feedstock was $31.65/ton (Statista, 2022). A conservative estimate of available biomass in standing unmarketable timber for this region (based on Fig. 4) is 16 tons/ac (assuming 70 metric tons of woody biomass per ha, half of which is unmarketable). Depending on many variables, especially transportation distance, this market for otherwise unmarketable standing timber might make timber stand improvement more economically feasible for landowners. Given these data, it is likely that development of a wood bioenergy industry in eastern Kentucky could reduce costs (and thus improve profits) for primary wood industries without existing residuals markets, as well as subsidize costs of silvicultural practices for hardwood timber stand improvement by providing a market for otherwise low-value or unmarketable timber species.

Table 5
Modeled social welfare impacts (in equivalent variation $), under modeled scenarios (increased intermediate demand of biomass for bioenergy production, as well as increased tariff rates on non-bioenergy-sourced electricity production).

Household annual income category	Number of households (% of total)	Modeled Scenarios		
		Low	Medium	High
Low ($0-40 K)	189,623 (56%)	68,613	137,276	285,770
Medium ($40-100 K)	114,110 (34%)	172,005	344,325	740,902
High ($ > 100 K)	35,547 (10%)	118,715	237,650	508,064

4.2. Economic analysis

A static CGE model was used to examine the potential economic impacts of increasing woody biomass for bioenergy or electricity production in the Appalachian region of Kentucky. It is observed that increased supply of woody biomass for bioenergy production at the expense of non-renewable energy sources increased net income of households marginally. Moreover, the analysis reveals a disproportionate net income impact between low-income and high-income households as high-income households experienced higher increase in net income relative to low-income households. Furthermore, increased intermediate demand of woody biomass for bioenergy production increased welfare impacts across all income categories. High income households received larger welfare impacts. Consequently, high-income households experienced a larger increase in utility.

It was observed that increased intermediate demand for woody biomass for bioenergy production led to increased supply price of commodities like agriculture, logging, wood product manufacturing, and bioenergy electricity generation (except for the low scenario). Supply price of commodities like natural gas and all other electricity generation reduced as a result of reduced demand following increased supply of bioenergy. The disproportionate impacts among the households by income categories could partly be attributed to these price impacts (Huang et al., 2012). Huang et al. (2012) found a decline in utility among low-income households following expansion of bioenergy production. They explained this could be resulting from a negative substitution effect which is greater than positive income effect, resulting from the increase in commodity supply prices like agriculture, logging, and pulp mill sectors. Though decline in net income or utility was not observed in this study, the small positive impact on low-income households can be explained by a negative substitution effect which was greater than the positive income effect due to increase in some commodity supply prices like agriculture and logging sectors. Further, the effect of increase in biomass supply on increase in commodity prices like agriculture and logging could place a higher burden on low-income households due to their higher dependence on agriculture and forest-related sectors relative to higher income household group. The disproportionate income impact can also be attributed to increase in income inequality among households.

Rural economic development policies that are intended to bridge income inequality gaps among households should be targeted to ensure low-income households do not suffer the unintended consequences of such policies as we have seen in this study where low-income households benefit the least from economic impacts disproportionately favoring high-income households. Low-income households could be provided with some form of financial assistance to cushion them from suffering extreme welfare losses. For example, they could be provided with some form of subsidies on energy-efficient appliances and home insulations to reduce their expenditures that may arise due to price increases. In this study, there is increase in bioenergy electricity prices under the medium and high scenarios. Specifically, expansion of woody biomass for electricity production under the medium and high scenarios increased the commodity supply price of bioenergy electricity generation by 0.016% and 0.056%, respectively. This would reduce utility of low-income households disproportionately relative to high income households.

Results show that increased biomass use for electric power generation would increase regional GDP, albeit marginally. A similar result was reported by Hodges et al. (2010) who used a CGE model to simulate expansion of biomass for bioenergy production in Florida that resulted in 0.32% increase in GDP. Similarly, Huang et al. (2012) reported a modest increase in GDP in Florida following an expansion of forest bioenergy production. Overall, our results are within the ballpark range of other related studies on the positive impact of woody biomass for bioenergy expansion on economic growth in southeast U.S. Increase in welfare impacts in our study partly conforms with Huang et al. (2012) who used a CGE model to investigate economic-wide and welfare impacts of increased forest bioenergy production in southeast U.S. The authors found that providing incentives for bioenergy production through tax reduction on a second-generation bioenergy sector increased the welfare of all income categories with high income households experiencing the largest welfare impacts. Moreover, Huang et al. (2012) observed that increase in technological production of bioenergy reduced welfare for low-income households while welfare of high-income households increased.

Increased demand for woody biomass has indirect ripple effects on other sectors that are not directly linked to bioenergy production. Increase in supply prices of agriculture and logging sectors increased their total output supply, however total output of wood product manufacturing sector declined. This finding aligns with Ochuodho et al. (2019) and Hodges et al. (2010). The decline of wood product manufacturing sector can be explained by competition the sector faces with bioenergy electricity generation sector for wood resources as intermediate inputs from the logging sector (Ochuodho et al., 2019; Hodges et al., 2010). In a recent report, USDA Forest Service cooperators and wood product researchers explained that increased demand for woody biomass would reduce production of wood products and use of timber resources would change (Nepal et al., 2019). However, increase demand for woody biomass for bioenergy would increase the economic value of trees which in turn would incentivize people to purchase forestland and harvest more trees (Nepal et al., 2019).

5. Conclusion and policy implications

In summary, this study assessed potential available woody biomass for bioenergy production and identified priority critical infrastructure sites where wood-residual fired CHP plants could be sufficiently supplied by available woody biomass. The study then assessed potential regional economic impacts of increased wood bioenergy production considering simulated increased intermediate input demand for woody biomass for electricity generation coupled with increased tariff rates on non-renewable energy production.

These analyses identified several hospitals as potentially suitable for establishing wood-fired CHP units. These sites were close enough to existing wood residual supplies (i.e., sawmills) that transportation of residuals to the sites was considered economically feasible. Furthermore, the estimated feedstock supply near these sites was sufficient to support consistent electricity production (5 days/wk), without tapping into the vast standing biomass resource available in low- or no-value standing timber resources. More comprehensive site-specific feasibility analyses will be necessary to evaluate economic feasibility of establishing CHP units on these sites, taking into consideration additional economic variables such as start-up costs (and the various grants, cost-share programs, and subsidies that offset them) and policy scenarios such as mandated renewable energy targets.

The study also revealed that economically exploiting available wood biomass to expand bioenergy production would have a positive impact on region's economy. This resulted in a modest increase in regional gross domestic product as well as increase in both federal and state government revenues. The study also revealed that expanding woody bioenergy production would result in a disproportionately positive welfare impact across households of different income levels, with low-income households having lower benefits. Conversely, expanding woody bioenergy production caused a decline in the wood products manufacturing sector as a result of increased competition for wood resources. Overall, expanding woody bioenergy production in the region will have a positive economic impact. More important for the forest sector, woody bioenergy development will create a much-needed market opportunity for low grade timber and forest industry residues that usually go wasted or unused. These positive impacts can only be realized if the state of Kentucky initiates programs or standards to promote woody bioenergy production. Currently, there are no renewable energy standards in Kentucky (Durkay, 2019), and the state is overly reliant on coal for its electricity production.

One limitation of this study was the lack of baseline data on energy production portfolio (by energy types) for the study region. The study obtained this data by using state-level intermediate demand values as a representation of the study region. This broad assumption of baseline may not give a true reflection of the study region values due to potential dissimilarities between regional and statewide data. Unlike the static CGE model employed in this study, which only provides a one-time snapshot, future studies can use a dynamic CGE model with well-defined projected future trends based on existing capacities to examine the economic and energy resilience transition path resulting from expansion of woody biomass for bioenergy production in the study region.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

The authors gratefully acknowledge the contributions of Dheeraj Betha and Jordan George, who provided invaluable assistance in distance estimation calculations and web design. This research was funded by the Kentucky Energy and Environment Cabinet (EEC) State Wood Energy Team (SWET), grant #1900003177.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.forpol.2022.102847.

References

[ARC] Appalachian Regional Commission, 2021. County Economic Status in Appalachia, FY 2022. https://www.arc.gov/map/county-economic-status-in-appalachia-fy-2022/ (Accessed 2 August 2021).
[DSIRE] Database of State Incentives for Renewables and Efficiency, 2020. NC Clean Energy Technology Center, NC State University. https://ncsolarcen-prod.s3.amazonaws.com/wp-content/uploads/2020/09/RPS-CES-Sept2020.pptx (Accessed 8 September 2022).
Abrams, M.D., 2003. Where has all the white oak gone? Bioscience 53 (10), 927–939. https://doi.org/10.1641/0006-3568(2003)053[0927:WHATWO]2.0.CO;2.
Abt, R.C., Abt, K.L., Cubbage, F.W., Henderson, J.D., 2010. Effect of policy-based bioenergy demand on southern timber markets: a case study of North Carolina. Biomass Bioenergy 34 (12), 1679–1686.
Abt, K.L., Abt, R.C., Galik, C., 2012. Effect of bioenergy demands and supply response on markets, carbon, and land use. For. Sci. 58 (5), 523–539.
Amichev, B.Y., Burger, J.A., Rodrigue, J.A., 2008. Carbon sequestration by forests and soils on mined land in the Midwestern and Appalachian coalfields of the US. For. Ecol. Manag. 256 (11), 1949–1959. https://doi.org/10.1016/j.foreco.2008.07.020.

Anagnostakis, S., 2001. The effect of multiple importations of pests and pathogens on a native tree. Biol. Invasions 3 (3), 245–254. https://doi.org/10.1023/A:1015205005751.
Andersson, E., Harvey, S., Berntsson, T., 2006. Energy efficient upgrading of biofuel integrated with a pulp mill. Energy 31 (10−11), 1384–1394. https://doi.org/10.1016/j.energy.2005.05.020.
Armington, P.S., 1969. A theory of demand for products distinguished by place of production. International Monetary Fund Staff Papers 16 (1), 159–178. https://doi.org/10.2307/3866403.
Bai, Y., Ochuodho, T.O., Yang, J., 2019. Impact of land use and climate change on water-related ecosystem services in Kentucky, USA. Ecol. Indic. 102, 51–64. https://doi.org/10.3390/land10010069.
Banerjee, O., Alavalapati, J.R.R., 2010. Illicit exploitation of natural resources: the forest concessions in Brazil. J. Policy Model 32 (4), 488–504. https://doi.org/10.1016/j.jpolmod.2010.06.001.
Banerjee, O., Alavalapati, J.R.R., 2014. Forest policy modelling in an economy-wide framework. In: Kant, S., Alavalapati, J.R.R. (Eds.), Handbook of Forest Resource Economics London. Taylor & Francis, England.
Bergman, L., 1988. Energy policy modeling: a survey of general equilibrium approaches. J. Policy Model 10 (3), 377–399. https://doi.org/10.1016/0161-8938(88)90028-2.
Binkley, C.S., Vertinsky, I.B., Thompson, W.A., Percy, M., 1994. A general equilibrium analysis of the economic impact of a reduction in harvest levels in British Columbia. For. Chron. 70 (4), 449–454. https://doi.org/10.5558/tfc70449-4.
Blackard, J.A., Finco, M.V., Helmer, E.H., Holden, G.R., Hoppus, M.L., Jacobs, D.M., Ruefenacht, B., 2008. Mapping US forest biomass using nationwide forest inventory data and moderate resolution information. Remote Sens. Environ. 112, 658–1677. https://doi.org/10.1016/j.rse.2007.08.021.
Butler, B.J., Butler, S.M., Caputo, J., Dias, J., Robillard, A., Sass, E.M., 2021. Family forest ownerships of the United States, 2018: results from the USDA Forest Service, national woodland owner survey. In: Gen. Tech. Rep. NRS-199. Madison, WI: US Department of Agriculture, Forest Service, northern Research Station. 52 p.[plus 4 appendixes], 199. https://doi.org/10.2737/NRS-GTR-199.
Catron, J.F., Stainback, G.A., Lhotka, J.M., Stringer, J., Hu, L., 2013. Financial and management implications of producing bioenergy in upland oak stands in Kentucky. North. J. Appl. For. 30 (4), 164–169. https://doi.org/10.5849/njaf.12-039.
Clarke, S.R., Riggins, J.J., Stephen, F.M., 2016. Forest management and southern pine beetle outbreaks: a historical perspective. For. Sci. 62 (2), 166–180. https://doi.org/10.5849/forsci.15-071.
Conrad, I.V., Joseph, L., 2018. Costs and challenges of log truck transportation in Georgia, USA. Forests 9 (10), 650. https://doi.org/10.3390/f9100650.
Deaton, B.J., Niman, E., 2012. An empirical examination of the relationship between mining employment and poverty in the Appalachian region. Appl. Econ. 44 (3), 303–312. https://doi.org/10.1080/00036846.2010.505558.
Dong, L., Liu, H., Riffat, S., 2009. Development of small-scale and micro-scale biomass-fuelled CHP systems–a literature review. Appl. Therm. Eng. 29 (11−12), 2119–2126. https://doi.org/10.1016/j.applthermaleng.2008.12.004.
Dornburg, V., Faaij, A.P., 2001. Efficiency and economy of wood-fired biomass energy systems in relation to scale regarding heat and power generation using combustion and gasification technologies. Biomass Bioenergy 21 (2), 91–108. https://doi.org/10.1016/S0961-9534(01)00030-7.
Drummond, M.A., Loveland, T.R., 2010. Land-use pressure and a transition to forest-cover loss in the eastern United States. Bioscience 60 (4), 286–298. https://doi.org/10.1525/bio.2010.60.4.7.
Dulys-Nusbaum, E., Klammer, S.S., Swinton, S.M., 2019. How willing are different types of landowner to supply hardwood timber residues for bioenergy? Biomass Bioenergy 122, 45–52. https://doi.org/10.1016/j.biombioe.2019.01.026.
Durkay, J., 2019. State Renewable Portfolio Standards and Goals, National Conference of State Legislatures (February 1, 2019). https://www.ncsl.org/research/energy/state-wind-energy-siting.aspx.
Espinoza, O., Mallo, M.F.L., Weitzenkamp, M., 2015. Overcoming barriers to biomass cogeneration in US wood products industry. Wood Fiber Sci. 47 (3), 295–312. https://wfs.swst.org/index.php/wfs/article/view/2325.
Evans, A., Strezov, V., Evans, T.J., 2010. Sustainability considerations for electricity generation from biomass. Renew. Sust. Energ. Rev. 14 (5), 1419–1427. https://doi.org/10.1016/j.rser.2010.01.010.
Exec. Order No. 14,008, 2021. Federal Register 86, 15pp.
Freudenburg, W.R., 1992. Addictive economies: extractive industries and vulnerable localities in a changing world economy. Rural. Sociol. 57 (3), 305–332. https://doi.org/10.1111/j.1549-0831.1992.tb00467.x.
Fricke, K., 2017. 8 considerations for benchmarking. Healthcare Design. https://healthcaredesignmagazine.com/trends/research-theory/8-considerations-benchmarking/ (Accessed 30 May 2019).
Furtenback, Ö., 2011. Dynamic CGE-model with heterogeneous forest biomass: Applications to climate policy, CERE - the Center for Environmental and Resource Economics. http://www.cere.se/documents/wp/CERE_WP2011-10.pdf.
Galik, C.S., Abt, R.C., Latta, G., Vegh, T., 2015. The environmental and economic effects of regional bioenergy policy in the southeastern US. Energy Policy 85, 335–346.
GAMS, 2012. (General Algebraic Modeling System)—Computer Application. GAMS Development Corporation, Washington, DC, USA. https://www.gams.com/ (Accessed 01 May 2019).
Gan, J., Smith, C.T., 2006. Availability of logging residues and potential for electricity production and carbon displacement in the USA. Biomass Bioenergy 30 (12), 1011–1020. https://doi.org/10.1016/j.biombioe.2005.12.013.
Gavrilescu, D., 2008. Energy from biomass in pulp and paper mills. Environ. Eng. Manag. J. 7 (5), 537–546. http://sawic.environment.gov.za/documents/12201.pdf.
Gillespie, G., McGregor, P.G., Swales, J.K., Yin, Y.P., 2001. The displacement of multiplier effects of regional selective assistance: a computable general equilibrium analysis. Reg. Stud. 35, 125–139. https://doi.org/10.1080/00343400120033115.
Grumman/Butkus Associates, 2017. "G/BA Releases 2016 Edition of Hospital Energy + Water Survey" (2017). Available online at. https://grummanbutkuscom/blog/post/g-ba-releases-2016-edition-of-hospital-energy-water-survey (Accessed 30 May 2019).
Haddad, S., Britz, W., Börner, J., 2017. Impacts of increased Forest biomass demand in the European bioeconomy Dept of production economics. In: Institute for Food and Resource Economics. Paper prepared for presentation at the 57th annual conference of the GEWISOLA (German Association of Agricultural Economists). University of Bonn, Germany. https://ageconsearch.umn.edu/record/261986/ (Accessed 10 May 2020).
Hansen, A.J., Neilson, R.P., Dale, V.H., Flather, C.H., Iverson, L.R., Currie, D.J., Shafer, S., Cook, R., Bartlein, P.J., 2001. Global changes in forests: responses of species, communities, and biomes. Bioscience 51 (9), 765–779. https://doi.org/10.1641/0006-3568(2001)051[0765:GCIFRO]2.0.CO;2.
Hicks, J., Ison, N., 2011. Community-owned renewable energy (CRE): opportunities for rural Australia. Rural. Soc. 20 (3), 244–255. https://doi.org/10.5172/rsj.20.3.244.
Hjerpe, E.E., Kim, Y.-S., 2008. Economic impacts of southwestern national forest fuels reductions. J. For. 106 (6), 311–316. https://doi.org/10.1093/jof/106.6.311.
Hodges, A.W., Stevens, T.J., Rahmani, M., 2010. Economic Impacts of Expanded Woody Biomass Utilization on the Bioenergy and Forest Products Industries in Florida (P 36) University of Florida. Institute of Food and Agricultural Sciences, Food and Resource Economics Department. https://fred.ifas.ufl.edu/pdf/economic-impact-analysis/Woody-Biomass-Utilization.pdf (Accessed 05 May 2020).
Hoffman, S., Fudge, S., Pawlisch, L., High-Pippert, A., Peters, M., Haskard, J., 2013. Public values and community energy: lessons from the US and UK. Sustain. 5 (4), 1747–1763. https://doi.org/10.3390/su5041747.
Holland, D., Stodick, L., Painter, K., 2007. Assessing the economic impact of energy price increases on Washington agriculture and the Washington economy: a general equilibrium approach, Working Paper 2007 14. https://ideas.repec.org/p/wsu/wpaper/holland-6.html (Accessed 05 May 2019).
Huang, M.Y., Alavalapati, J.R., Banerjee, O., 2012. Economy-wide impacts of forest bioenergy in Florida: a computable general equilibrium analysis. Taiwan J For Sci 27 (1), 81–93.
Hudson, B., 2018. Fighting fire with fire: adjusting regulatory regimes and forest product markets to mitigating southern United States wildfire risk. J Envtl L and Litigation 33. https://ssrn.com/abstract=3179338.
Hughes, E., 2000. Biomass cofiring: economics, policy and opportunities. Biomass Bioenergy 19 (6), 457–465. https://doi.org/10.1016/S0961-9534(00)00057-X.
Iakovou, E., Karagiannidis, A., Vlachos, D., Toka, A., Malamakis, A., 2010. Waste biomass-to-energy supply chain management: a critical synthesis. Waste Manag. 30 (10), 1860–1870. https://doi.org/10.1016/j.wasman.2010.02.030.
Inflation Reduction Act, 2022. Pub L. No. 117-169. https://www.congress.gov/bill/117th-congress/house-bill/5376/text.
Johansen, L., 1960. A Multi-Sectoral Study of Economic Growth. North-Holland Publishing Company, Amsterdam, The Netherlands, p. 1960.
Junginger, M., Faaij, A., van den Broek, R., Koopmans, A., Hulscher, W., 2001. Fuel supply strategies for large-scale bio-energy projects in developing countries: electricity generation from agricultural and forest residues in northeastern Thailand. Biomass Bioenergy 21 (4), 259–275. https://doi.org/10.1016/S0961-9534(01)00034-4.
Kallio, A.M.I., Salminen, O., Sievänen, R., 2013. Sequester or substitute—consequences of increased production of wood based energy on the carbon balance in Finland. J. For. Econ. 19 (4), 402–415.
Kelsey, K.C., Barnes, K.L., Ryan, M.G., Neff, J.C., 2014. Short and long-term carbon balance of bioenergy electricity production fueled by forest treatments. Carbon Balance Manag 9 (1), 6. https://doi.org/10.1186/s13021-014-0006-1.
Kentucky Division of Geographic Information (DGI) (2018) KY Hospitals, Kentucky Open GIS Data (2018) HYPERLINK "http://kygovmaps-kygeonetopendataarcgiscom/datasets/527112a2cbbd4dae8e87311f47297f26_0?geometry=−9607%2C37676%2C-85731%2C40239https://appsfsusdagov/fia/datamart/datamart_accesshtml" http://kygovmaps-kygeonetopendataarcgiscom/datasets/527112a2cbbd4dae8e87311f47297f26_0?geometry=−9607%2C37676%2C-85731%2C40239https://appsfsusdagov/fia/datamart/datamart_accesshtml ((Accessed 30 May 2019) DataMart v FIADB_17001 Available online at Accessed 30 May 2019).
King, M., 2014. Feasibility Study of a Woody-Biomass-Based Combined Heat and Power Utility at Wind River Business Park in Hemlock. WA Final project report prepared by WR Community Solutions Inc, for Port of Skamania County, March 2014. Available online at. https://portofskamaniaorg/wp-content/uploads/2017/08/Skamania-FS-FINAL1pdf.
Korhonen, J., Wihersaari, M., Savolainen, I., 2001. Industrial ecosystem in the Finnish forest industry: using the material and energy flow model of a forest ecosystem in a forest industry system. Ecol. Econ. 39 (1), 145–161. https://doi.org/10.1016/S0921-8009(01)00204-X.
Laitner, J.A., Donald, A., Hanson, D.A., 2006. Modeling detailed Energy-efficiency technologies and technology policies within a CGE framework. Energy J. 27, 151–169. https://doi.org/10.5547/ISSN0195-6574-EJ-VolSI2006-NoSI2-8.
Law, J., McSweeney, K., 2013. Looking under the canopy: rural smallholders and forest recovery in Appalachian Ohio. Geoforum 44, 182–192. https://doi.org/10.1016/j.geoforum.2012.09.008.
Leino, M., Uusitalo, V., Grönman, A., Nerg, J., Horttanainen, M., Soukka, R., Pyrhönen, J., 2016. Economics and greenhouse gas balance of distributed electricity

production at sawmills using hermetic turbogenerator. Renew. Energy 88, 102–111. https://doi.org/10.1016/j.renene.2015.11.029.

Lobao, L., Zhou, M., Partridge, M., Betz, M., 2016. Poverty, place, and coal employment across Appalachia and the United States in a new economic era. Rural. Sociol. 81 (3) https://doi.org/10.1111/ruso.12098, 343–38.

Lofgren, H., Harris, R.L., Robinson, S., Thomas, M., EI-Said, M., 2002. Microcomputers in Policy Research 5. IFPRI, Washington, DC.

Lu, C., Zhang, X., He, J., 2010. A CGE analysis to study the impacts of energy investment on economic growth and carbon dioxide emission: a case of Shaanxi Province in western China. Energy 5 (11), 4319–4327. https://doi.org/10.1016/j.energy.2009.04.007.

MacFarlane, D.W., 2009. Potential availability of urban wood biomass in Michigan: implications for energy production, carbon sequestration and sustainable forest management in the USA. Biomass Bioenergy 33 (4), 628–634. https://doi.org/10.1016/j.biombioe.2008.10.004.

Maxwell, A.E., Strager, M.P., Yuill, C.B., Petty, J.T., 2012. Modeling critical Forest habitat in the southern coal fields of West Virginia. Int J Ecol 2012, 1–10. https://doi.org/10.1155/2012/182683.

McGowin, C.R., Wiltsee, G.A., 1996. Strategic analysis of biomass and waste fuels for electric power generation. Biomass Bioenergy 10 (2–3), 167–175. https://doi.org/10.1016/0961-9534(95)00070-4.

McIlmoil, R., Hansen, E., 2010. The Decline of Central Appalachian Coal and the Need for Economic Diversification, Thinking Downstream: White Paper 1. https://motherjones.com/files/DownstreamStrategies-DeclineOfCentralAppalachianCoal-FINAL-1-19-10.pdf.

McIlveen-Wright, D., Williams, V., McMullan, J., 2001. A re-appraisal of wood-fired combustion. Bioresour. Technol. 76 (3), 183–190. https://doi.org/10.1016/S0960-8524(00)00129-2.

McLellan, B., Zhang, Q., Farzaneh, H., Utama, N.A., Ishihara, K.N., 2012. Resilience, sustainability and risk management: a focus on energy. Chall 3 (2), 153–182. https://doi.org/10.3390/challe3020153.

Miller, M.H., Spencer, J.E., 1977. The static economic effects of the UK joining the EEC: a general equilibrium approach. Rev. Econ. Stud. 38, 175–208. https://doi.org/10.2307/2296974.

Murphy, F., Devlin, G., McDonnell, K., 2015. Greenhouse gas and energy based life cycle analysis of products from the Irish wood processing industry. J. Clean. Prod. 92, 134–141. https://doi.org/10.1016/j.jclepro.2015.01.001.

Nepal, P., Abt, K.L., Skog, K.E., Prestemon, J.P., Abt, R.C., 2019. Projected market competition for wood biomass between traditional products and energy: a simulated interaction of US regional, national, and global forest product markets. For. Sci. 65 (1), 14–26. https://doi.org/10.1093/forsci/fxy031.

Ochuodho, T.O., Alavalapati, J.R., Lal, P., Agyeman, D.A., Wolde, B., Burli, P., 2019. Potential economic impacts of allocating more land for bioenergy biomass production in Virginia. Forests 10 (2), 159. https://doi.org/10.3390/f10020159.

Ovaskainen, V., Hänninen, H., Mikkola, J., Lehtonen, E., 2006. Cost-sharing and private timber stand improvements: a two-step estimation approach. For. Sci. 52 (1), 44–54. https://doi.org/10.1093/forestscience/52.1.44.

Ovaskainen, V., Hujala, T., Hänninen, H., Mikkola, J., 2017. Cost sharing for timber stand improvements: inducement or crowding out of private investment? Forest Policy Econ. 74, 40–48. https://doi.org/10.1016/j.forpol.2016.10.014.

Perez-Verdin, G., Grebner, D.L., Munn, I.A., Sun, C., Grado, S.C., 2008. Economic impacts of woody biomass utilization for bioenergy in Mississippi. For. Prod. J. 58 (11), 75–83.

Pyatt, G., Round, J.I. (Eds.), 1985. Social Accounting Matrices: A Basis for Planning. The World Bank, Washington, DC. https://agris.fao.org/agris-search/search.do?recordID=US2012418990 (Accessed 06 June 2019).

Quesada-Pineda, H., Wiedenbeck, J., Bond, B., 2016. Analysis of electricity consumption: a study in the wood products industry. Energy Effic 9 (5), 1193–1206. https://doi.org/10.1007/s12053-015-9417-4.

Raunikar, R., Buongiorno, J., Turner, J.A., Zhu, S., 2010. Global outlook for wood and forests with the bioenergy demand implied by scenarios of the intergovernmental panel on climate change. Forest Policy Econ. 12 (1), 48–56.

Rickman, D.S., 1992. Estimating the impacts of regional business assistance programs: alternative closures in a regional model. Pap. Reg. Sci. 71, 21–35. https://doi.org/10.1007/BF01434466.

Robinson, S., El-Said, M., 2000. GAMS Code for Estimating a Social Accounting Matrix (SAM) Using Cross Entropy Methods (CE). International Food Policy Research Institute (IFPRI) (Accessed on 06 June 2019).

Robinson, S., Roland-Holst, D.W., 1988. Macroeconomic structure and computable general equilibrium models. J. Policy Model 10, 353–375. https://doi.org/10.1016/0161-8938(88)90027-0.

Robinson, S., Cattaneo, A., El-Said, M., 2001. Updating and estimating a social accounting matrix using cross entropy methods. Econ. Syst. Res. 13 (1), 47–64. https://doi.org/10.1080/09535310120026247.

Saidur, R., Abdelaziz, E., Demirbas, A., Hossain, M., Mekhilef, S., 2011. A review on biomass as a fuel for boilers. Renew. Sust. Energ. Rev. 15 (5), 2262–2289. https://doi.org/10.1016/j.rser.2011.02.015.

Saul, D., Newman, S., Peterson, S., Kosse, E., Jacobson, R., Keefe, R., Moroney, J., 2018. Evaluation of three Forest-based bioenergy development strategies in the inland northwest. United States. J For 116 (6), 497–504. https://doi.org/10.1093/jofore/fvy042.

Sedjo, R., Tian, X., 2012. Does wood bioenergy increase carbon stocks in forests? J. For. 110 (6), 304–311.

Shivan, G.C., Sayeed, R. Mehmood, 2010. Factors influencing nonindustrial private forest landowners' policy preference for promoting bioenergy. Forest Policy and Economics 12 (8), 581–588.

Shoven, J.B., Whalley, J., 1972. A general equilibrium calculation of the effects of differential taxation of income from capital in the US. J. Public Econ. 1 (3–4), 281–321. https://elischolar.library.yale.edu/cgi/viewcontent.cgi?article=1560&context=cowles-discussion-paper-series (Accessed 06 June 2019).

Söderberg, C., Eckerberg, K., 2013. Rising policy conflicts in Europe over bioenergy and forestry. Forest Policy Econ. 33, 112–119.

Statista, 2019. Average monthly price of biomass feedstocks in the US as of January 2018, by region (in US dollar per metric ton). https://www.statista.com/statistics/499514/biomass-feedstock-prices-in-the-us-by-region/ (Accessed 26 July 2019).

Statista, 2022. Average price of biomass feedstocks in the United States as of March 2022, by product. https://www.statista.com/statistics/856660/biomass-feedstock-prices-in-the-us-by-product/ (Accessed 8 September 2022).

Stone, R., 1954. Linear expenditure systems and demand analysis: an application to the pattern of British demand. Econ. J. 64, 511–527. https://doi.org/10.2307/2227743.

Taheripour, F., Hertel, T.W., Tyner, W.E., Beckman, J.F., Birur, D.K., 2010. Biofuels and their by-products: global economic and environmental implications. Biomass Bioenergy 34 (3), 278–289. https://doi.org/10.1016/j.biombioe.2009.10.017.

Taylor, B., Hufford, M., Bilbrey, K., 2017. A green new deal for Appalachia: economic transition, coal reclamation costs, bottom-up policymaking (part 1). J Appalach Stud 23 (1), 8–28. https://doi.org/10.5406/jappastud.23.1.0008.

UN [United Nations] (Statistical Division), 2008. The System of National Accounts 2008. New York, US. https://unstats.un.org/unsd/nationalaccount/sna2008.asp (Accessed 05 April 2019).

US Department of Agriculture (UDSA), 2019. Forest Service Forest Inventory Analysis (FIA). https://www.fia.fs.fed.us/ (Accessed 05 May 2019).

US Department of Agriculture, Forest Service (USDA-FS), 2019. "Forest Biomass across the Lower 48 States and Alaska" FSGeodata Clearinghouse Available online at. https://datafsusdagov/geodata/rastergateway/biomass/ (Accessed 30 May 2019).

US Energy Information Administration (US EIA), 2022a. Monthly Energy Review, Table 1.2: "Primary Energy Production by Source". https://www.eia.gov/totalenergy/data/monthly/pdf/sec1_5.pdf (Accessed 8 Sept 2022).

US Energy Information Administration (US EIA), 2022b. Monthly Energy Review, Table 10.1: "Renewable Energy Production and Consumption by Source.". https://www.eia.gov/totalenergy/data/monthly/pdf/sec10_3.pdf (Accessed 8 Sept 2022).

US Energy Information Adminstation (US EIA), 2019a. Electricity Data Browser, Net Generation for all Sectors (Thousand Megawatthours), Kentucky, Annual, pp. 2001–2018. https://www.eia.gov/electricity/data.php (Accessed 05 June 2019).

US Energy Information Adminstation (US EIA), 2019b. Southern States Lead Growth in Biomass Electricity Generation. https://wwweiagov/todayinenergy/detailphp?id=26392 (Accessed 26 July 2019).

US Energy Information Adminstration (US EIA), 2019. Monthly Energy review, Table 13 and 101, April 2018, Preliminary Data. http://large.stanford.edu/courses/2018/ph241/green1/docs/doe-eia-0035-2018-4.pdf (Accessed 05 June 2019).

USDA, 2018. Timber Product Output (TPO) Reports. https://wwwfsusdagov/srsfia/php/tpo_2009/tpo_rpa_int1php (Accessed 26 Oct 2018).

USDOE, 2004. Biomass Energy-Focus on Wood Waste. US Department of Energy Washington, DC. USA. https://www.nrc.gov/docs/ML1409/ML14093A260.pdf (Accessed 12 May 2019).

Valentine, S.V., 2011. Emerging symbiosis: renewable energy and energy security. Renew. Sust. Energ. Rev. 15 (9), 4572–4578. https://doi.org/10.1016/j.rser.2011.07.095.

van den Broek, R., Teeuwisse, S., Healion, K., Kent, T., van Wijk, A., Faaij, A., Turkenburg, W., 2001. Potentials for electricity production from wood in Ireland. Energy 26 (11), 991–1013. https://doi.org/10.1016/S0360-5442(01)00050-0.

van Hoesen, J., Letendre, S., 2010. Evaluating potential renewable energy resources in Poultney, Vermont: a GIS-based approach to supporting rural community energy planning. Renew. Energy 35 (9), 2114–2122. https://doi.org/10.1016/j.renene.2010.01.018.

Viana, H., Cohen, W.B., Lopes, D., Aranha, J., 2010. Assessment of forest biomass for use as energy: GIS-based analysis of geographical availability and locations of wood-fired power plants in Portugal. Appl. Energy 87 (8), 2551–2560. https://doi.org/10.1016/j.apenergy.2010.02.007.

Wang, Y., Ma, W., Farlee, L.D., Jackson, E.A., Shao, G., Ochuodho, T., Liang, J., Zhou, M., 2021. Assessing the benefits and economic feasibility of stand improvement for central hardwood forests. For. Sci. 67 (3), 297–311. https://doi.org/10.1093/forsci/fxaa057.

Wetterlund, E., Pettersson, K., Harvey, S., 2011. Systems analysis of integrating biomass gasification with pulp and paper production–effects on economic performance, CO2 emissions and energy use. Energy 36 (2), 932–941. https://doi.org/10.1016/j.energy.2010.12.017.

Winston, R.A.P., 2009. Enhancing Agriculture and Energy Sector Analysis in CGE Modelling: An Overview of Modifications to the USAGE Model. Monash University, Centre of Policy Studies and the Impact Project. https://vuir.vu.edu.au/38930/1/g-180.pdf (Accessed on 10 June 2020).

Wu, J., Wang, J., McNeel, J., 2011. Economic modeling of woody biomass utilization for bioenergy and its application in central Appalachia, USA. Can. J. For. Res. 41 (1), 165–179.

Zambelli, P., Lora, C., Spinelli, R., Tattoni, C., Vitti, A., Zatelli, P., Ciolli, M., 2012. A GIS decision support system for regional forest management to assess biomass availability for renewable energy production. Environ. Model. Softw. 38, 203–213. https://doi.org/10.1016/j.envsoft.2012.05.016.

Zipper, C.E., Burger, J.A., McGrath, J.M., Rodrigue, J.A., Holtzman, G.I., 2011a. Forest restoration potentials of coal-mined lands in the eastern United States. J. Environ. Qual. 40 (5), 1567–1577. https://doi.org/10.2134/jeq2011.0040.

Zipper, C.E., Burger, J.A., Skousen, J.G., Angel, P.N., Barton, C.D., Davis, V., Franklin, J. A., 2011b. Restoring forests and associated ecosystem services on appalachian coal surface mines. Environ. Manag. 47 (5), 751–765. https://doi.org/10.1007/s00267-011-9670-z.